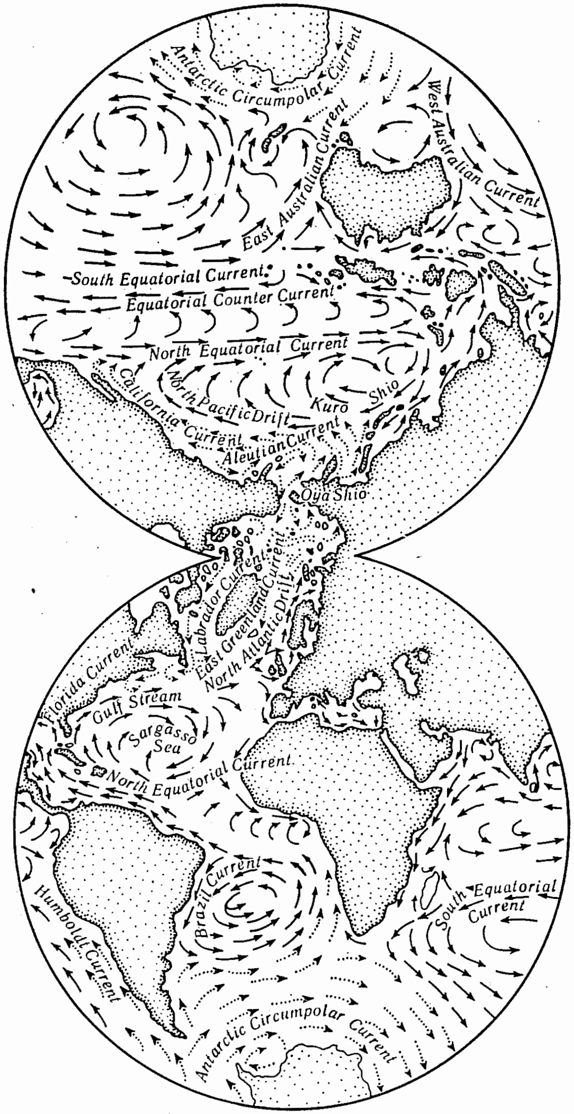
Man's attempts to control the weather and improve the climate over vast territories date back to ancient times. This desire was reflected in folklore, the Bible and folk legends, ritual "rain dances" and historic documents. Scientists, too, contributed their efforts to finding the causes of climatic changes. Various projects for the improvement of climate were advanced time and again. The problem was approached in different ways. It was suggested, for example, to destroy the ice in the Arctic Ocean and thus save many countries in the moderate and northern latitudes from the ill effects of Arctic cold. Today the problem is acquiring practical importance. Having objectively analysed paleogeographic data, the author of this book, Soviet engineer P. Borisov, challenges the idea that the conservatism and inertia of climate cannot be overridden. He claims that the reconversion of climate is one of the most important international and social problems. P. Borisov is confident that there is a great future in store for his project which envisages a complex of hydrotechnical installations to create a direct flow of Atlantic waters through the Arctic Ocean, which could thus prevent the formation of the ice cover in the Arctic Basin.



P. Borisov

can man change the climate?

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П. Борисов

МОЖЕТ ЛИ ЧЕЛОВЕК
ИЗМЕНИТЬ КЛИМАТ?

На английском языке

REQUEST TO READERS

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a number of objections that had been raised against it. However, a good deal of it is still debatable and obscure. The reaction of Nature over vast territories to the change in glaciation of the Arctic Basin cannot as yet be determined, nor can this reaction be taken for granted. For example, in the 1930s-1940s, when the glaciation of the northern seas sharply decreased, the level of the Caspian Sea dropped drastically, while that of the Aral Sea rose. We are uncertain as to what will happen if we do away with permafrost, etc.

The many questions that must be answered to solve so tremendous a problem as the planetary melioration of the climate can scarcely be enumerated. However, there are reasons to assert that this problem is acquiring very real and tangible substance. Doubtless reader will be greatly interested in this book. The author's research has made a great contribution to the advancement of this question.

S. Y. Geller,
Dr. Sc. (Geography)

...UNTIL WE KNOW A LAW OF NATURE, IT, EXISTING AND ACTING INDEPENDENTLY OF AND OUTSIDE OUR MIND, MAKES US SLAVES OF "BLIND NECESSITY". BUT ONCE WE COME TO KNOW THIS LAW, WHICH ACTS (AS MARX REPEATED A THOUSAND TIMES) *INDEPENDENTLY* OF OUR WILL AND OUR MIND, WE BECOME THE MASTERS OF NATURE.

V. I. LENIN

THE TROUBLES OF OUR CLIMATE

On account of her long shoreline Russia appears to stretch along the coastline of the Arctic Ocean.

D. I. Mendeleyev

The breath of the Arctic Ocean restrains the economic activities of many countries situated in the moderate and polar latitudes of the Northern Hemisphere. It restrains them primarily by low temperatures and long winters.

In the west and, especially, in the south and east the USSR is protected by mountain chains which hinder the penetration of heat and moisture, whereas in the north it is widely open to the cold and heavy masses of air which, having formed over the vast expanses of the Arctic ice sheet freely spread over the country's unprotected plains. The absence of latitudinally-stretching mountains on the territory of North America causes the masses of air cooled in the Arctic similarly to penetrate as far as to the area of the Great Lakes, the Great Plains and further to the Gulf of Mexico.

On the territory of the USSR the Arctic causes protracted winters, as well as late spring and early autumn frosts, thus shortening the vegetative season. Consequently the length of time for field work is limited by the weather, largely dependent on Arctic glaciation. Therefore the work is executed under great pressure, often giving rise to the concept of "a day feeds a year". It is understandable that under these conditions a crop can only be considered grown after it has been garnered.

In 1892 A. I. Voyeikov, the founder of Russian climatology, wrote: "Our rigorous winter and short summer are a disadvantage to our national economy; they hinder us

from cultivating the plants of warmer countries, and force every farmer to keep additional animals and implements. Also they have to spend more money on heating and warm clothes as compared with the West European farmer."

Even the southernmost territories of the Central Asian and Transcaucasian Soviet Republics are not protected from the cold air. In 1924 a wave of cold Arctic air reached Western Georgia and within a few days destroyed the tangerine, orange and other subtropical plants.

In February 1929 a cold air stream penetrated the European part of the USSR, took in the Crimea and the Caucasus, reached Turkey and through the Syrian Desert to Arabia. On the Black Sea coast of the Crimea the temperature dropped to minus 25°C and on the Caucasian coast to minus 10°C, many vineyards and citrus plantations being destroyed as a result.

In February 1949 Arctic air invaded Transcaucasia, Central Asia, Turkey and Iran. In Tashkent the temperature dropped to minus 30°C, hundreds of people froze to death in Iran, while the streets of Jerusalem were covered with a 60-cm coat of snow. In Georgia the citrus plantations were greatly damaged with the result that even 11 years later the sale of citrus fruit to the State amounted to only 73 per cent of that preceding the catastrophe.

In the winter of 1962-1963 cold Arctic air reached the northern continents—all of Europe, Asia including Turkey, and North America as far as Florida. It became colder and the glaciation in the Arctic seas increased. Avalanches of icy Arctic air gained momentum in the second half of December and permeated the warm southern latitudes. The intensive cooling was maintained by a stabilised snow coat. In January the avalanches increased, the temperature dropping to minus 36°C in the USA (Colorado), minus 39°C in Switzerland and to minus 17°C in Toulouse, where frost is almost unknown. On the Azure Coast and in Marseilles the palm trees were covered with snow. All the West-European rivers and Venetian canals were icebound. Between January 3 and 5 more than 700 people froze to death in Western Europe.

During the same winter low temperatures were for a long time recorded in many regions of the USSR. In Moscow the frosts reached minus 30°C and in Narofominsk (Moscow

Region) minus 38°C. Abnormal frosts, some days reaching minus 37°C, affected the north of Moldavia and some parts of the Ukraine. Odessa was in the grip of frosts dropping to 20°C below zero, the port being icebound and covered with snow. Severe ice conditions persisted in the spring in many Northern seas, especially in the Barents, White and Baltic seas. Spring set in very late. Cold air often invaded the continent from the Arctic Basin, and all through March and the first ten days of April winter conditions prevailed in the European part of the USSR. In Volgograd Region and the greater part of Rostov Region the temperature dropped to minus 38°C, and from March 11 to 20 despite a thin coat of snow masses of cold air spread over the Central Asian Republics.

As frequently happens when spring is delayed, the cold weather was superseded by a sharp rise in temperature, and the resulting melted snow could not soak into the frozen soil, and was carried away to rivers and other reservoirs, creating a false impression of having abundantly watered the fields. The winter crops, mainly wheat, were either destroyed or so thinned out that large areas had to be sown anew with different crops.

The spring was followed by a hot and dry summer; thus much less grain was garnered than had been planned for. As in all the other droughty years the country suffered enormous losses in livestock, as well as in the food and light industries. In 1963 the increase in national income was 6,800 million rubles as against 14,300 million and 15,700 million rubles in the 1958 and 1964 bumper-crop years.

The Siberian frosts are also to a great extent connected with the Arctic. When an Asian winter anticyclone receives enough nourishment from the north through the influx of masses of Arctic air the continental masses of air forming in the Arctic become particularly cold, and move westwards. They move somewhat less freely towards the Pacific, where they form the winter monsoons of the Far East. It is more difficult for them to penetrate to the warm south because they have to surmount the high South-Asian mountains.

It was not without reason that Voyeikov wrote, with bitterness, in 1911: "As vast as Russia is we have very few warm climates." As a matter of fact, 35 per cent of the territory of the USSR is covered with Arctic and thin-forest

tundras, 47 per cent with permafrost, at least 75 per cent is periodically cooled to minus 40°C and lower, and even the more temperate areas of Transcaucasia and the Crimea are not spared temperatures of minus 20°C. Permafrost also dominates North America, 60 per cent of the territory of Canada and 70 per cent of Alaska.

Agriculture is not only affected by frosts and protracted winters but also by the cold and therefore dehydrated mass of Arctic air which becomes heated while migrating southwards. The higher the temperature of the air the more moisture is required for its saturation. The lack of moisture leads to desiccation of the vegetative cover and the soil. Under certain synoptical conditions desiccation goes so far that the masses of cold air become heated and cause dry winds and droughts—the bane of agriculture. Soviet Academicians Gerasimov and Markov noted that at the present time a mere increase in the glaciation of the Arctic Basin causes ... drought in the Ukraine and the Volga areas.

Early in 1971 the *Newsweek* reported a drought that overtook the farmers of the American South. This drought was very similar to the 7-year drought of the 1950s and federal aid had to be sought by the Governors of Texas and Oklahoma for the many counties afflicted in their respective states. The absence of fodder forced the owners of cattle ranches to drive their cattle to market. Many South-Texan farmers were in danger of losing half their year's income. The greatest pecuniary losses were suffered by the unirrigated Texas farms.

The history of agriculture of pre-revolutionary Russia and the first post-revolutionary years is one of almost continuous scarcity with very few bumper crops. As a result of droughts between 1889 and 1921, 20 of the 33 years were years of dearth! Intensive droughts caused epidemics and loss of cattle on a mass scale as well as a high mortality.

During the bad-crop year of 1901 V. I. Lenin wrote: "Again famine! The last ten years have been marked, not only by the ruin of the peasantry, but by its veritable extinction, which has proceeded with such an astonishing rapidity that no war, however prolonged and bitter, has claimed such a host of victims."*

* V. I. Lenin, *Collected Works*, Vol. 5, p. 253.

Even the tsarist Ministry of the Interior had to admit in 1908: "Every year a large number of Russian peasants were faced with the possibility of starving to death."

In Latin American countries, and in India and Turkey droughts cause famine and the extinction of the population in great numbers. There is justification for the saying that a victory over drought is equal to winning a major battle.

The climate of the Soviet Union is extraordinarily unpredictable. For example, on January 28, 1956, in the centre of the Arctic Basin, on the North Pole-5 drifting station there was 41°C below zero, while two days later the temperature rose almost to the point of thawing, i.e., minus 1°C. On January 31 of the same year an identical temperature—minus 4°C—was recorded on the same polar station and in Sochi, on the Black Sea coast. The rise in temperature to minus 1°C in the dead of winter is the more remarkable since the temperature in Moscow at that time was minus 30°C.

The instability of the temperature can also be seen from the data of widespread long-term observations. The mean January temperature in Moscow is minus 10.3°C, but some years it only drops to minus 3°C, the usual temperature of a southern city such as Odessa, although it quite often drops to 22°C below zero, a temperature typical of North Spitsbergen, Franz Josef Land and the northernmost point of Novaya Zemlya (Fig. 1). The same situation can be observed in Leningrad where the mean January temperature may vary between minus 24.4°C and plus 0.6°C.

The instability of the climate is not confined to annual or even perennial fluctuations. Fluctuation on a still larger scale has been noted over many centuries. Thus the amount of annual rainfall in the Altai plains has changed from 160 mm in the 1860s to 500 mm in the present century.

If we could visualise that without human intervention, during the span of one or two generations the landscape could change from desert to forest-steppe or vice versa—only then can this be compared with the fluctuations of the climate of the USSR.

In the far distant past even greater degrees of extremes were recorded. According to Russian chroniclers, on July 2, 1454, "a frost beat down the rye", while in 1485 "during the two months of January and February it was so warm that

trees in the orchards sprouted and flowered, and the grass grew tall and the birds built nests". In 1524 the snow did not melt until May 25, and instead of ploughing starting in April, as usual, it had to be postponed until June. As an

Fig. 1. The margins of fluctuation in mean January temperatures in Moscow (isotherms —22° and —3°)

example of the instability of the climate, special mention should be made of the 25-year drought that befell the country in the 14th century.

The dependence of the severe coolings and droughts on the extent of glaciation of the Arctic Basin is constant enough if we trace this dependence over long periods of time, i.e., centuries. Some years, however, this dependence is disturbed because the changes in the circulation of the masses of water of the World Ocean and the Earth atmosphere may cause large deviations from the mean weather conditions—sharp frosts in July and protracted thaws in January. The greater the temperature difference between the equator and the pole, the more unquiet the atmospheric conditions and the greater the frequency and scope of deviations. That is why during the periods when the Arctic Basin was particularly well packed with ice, as for example, in the

14th and 15th centuries, more frequent were the protracted winters, droughts and storms with more years of scarcity and famine as a result.

But cold harms not only agriculture. In some measure or other it restrains all of man's productive activity. The farther north one goes, the greater are the strain and expenses on construction and transport, and indeed on industry itself. The Arctic Basin itself is accessible to navigation 2-4 months a year and only in the littoral zone.

However, as the economy of the Soviet Union develops and incidentally, also that of Canada and the United States of America, more investments are made with each passing year in the northern and eastern areas where there are large deposits of a wide range of minerals. The Soviet Union distributes part of its productive forces in Siberia where three-quarters of the country's total coal reserves and 85 per cent of its hydro-power are concentrated, where numerous oil and gas deposits have been discovered and where there are many areas with a high concentration of natural resources which can be profitably exploited.

On the whole the sub-Arctic and Arctic are becoming important areas to the oil and gas industries. In the USSR this situation is quite evident. In Canada prospecting has extended to the islands nearest the North Pole. Alaska is already one of the important oil regions of the USA. In recent years geophysical prospecting has brought to light very rich gas and oil deposits in vast areas of the Arctic coast and shelf.

Extensive construction of metallurgical, chemical and engineering enterprises, automobile and railway building, as well as various power-intensive industries of world importance, have now been launched in Siberia. In addition to the industrialisation of vast territories from the Urals to the Pacific, new towns are being built and reconstruction work is being carried out to the old towns. And all this is taking place in Siberia which is known as the coldest region of the Northern Hemisphere.

A number of specific difficulties, due to rigorous natural conditions, are experienced by the unprecedented industrialisation of this vast territory. Long years of experience have taught the USSR, the USA and Canada, that given identical technical facilities, the cost of production under north-

ern conditions is several times higher than in the middle latitudes. Only the very large reserves and the concentration of natural resources justify the additional high expenditure.

For lack of economic means of communication the timber and mineral resources of the eastern areas are poorly exploited. For example, the vast, but sparsely populated territory of Yakutia with its diamonds, oil, gas and coal has no railways, although it covers 15 per cent of the total area of the USSR. The rivers of Yakutia (like all the other rivers of Siberia) are not joined and flow in a northern direction to the scarcely navigable Arctic Basin. And an extensive use of modern aviation is as yet uneconomic and would require considerable expenditures because of the sparse population and rigorous conditions. The same applies to Eastern Siberia, which accounts for one-third of the area and 3 per cent of the population of the USSR, although its raw material and power resources exceed even those of so rich an industrial area as the Urals.

During the cold season a larger part of the USSR is under snow. With a few exceptions, the rivers and many reservoirs of the European part of the USSR, to say nothing of Siberia, are icebound and water transport is tied up for six months or more. And life ebbs low in most of the Soviet seaports—on the Sea of Azov, the Baltic and the White seas, and all along the Arctic coast to Vladivostok—because there is no free access to them during the long freeze-up.

With the extraordinarily low temperatures, high winds and heavy snows, buildings and transport and civil facilities need to be extra strong, so all construction becomes more expensive.

It will be remembered that labour is at its most productive at a temperature of 15 to 26°C and temperatures for a maximum development of the vegetation are between 25 and 30°C throughout the year, very different from the conditions which obtain in the USSR, Canada and Alaska. The losses inflicted by frosts are so great that they are becoming intolerable. That is why the task which the Communist Party of the Soviet Union has set Soviet science—reducing to the minimum the dependence of the economy on natural elements and elaborating methods of influencing the climatic conditions—is of such great economic importance.

The expenditures connected with the cold climate are increasing all the time, and they have now reached a point where it might well be much cheaper and easier to deal with the causes of the disease than to control it. But before one starts to treat a disease, it is necessary to find out the causes of its onset and to chart its development. In other words, before improving the climate, one must know what it was like in the near and distant past, establish some regular pattern of its development, especially during the more recent stages of the geological history of the Earth and then, on the basis of these regularities, find a reliable and constructive method of improving it.

CLIMATES IN THE DISTANT PAST (70 MILLION-500,000 YEARS AGO)

...The North Pole was not always cold because ocean currents passed over it bringing large amounts of warmth.

P. P. Lazarev

Our planet is more than 5,000 million years old. Its climate has changed many times. But we need not go too far back into times about which we have very little information. During the last few hundred million years, on which geological and paleogeographic information is fairly complete and reliable, there have been great variations in the climate. There have been periods of extreme cold and continental glaciation, similar to the glacial period in which we are living. But these extreme fluctuations were very rare. They include the glaciation of the Paleozoic era (about 200 million to 220 million years ago) and three or four older glacial periods. Lesser drops in temperature, with glaciation of some high mountain systems farther away from the equator occurred much more often. However, no single drop in temperature lasted very long. The present glacial period, plus the interglacial periods, are estimated at only half a million years. Mild climatic conditions, on the other hand, lasted hundreds of times as long. So we are justified in believing that a mild climate, much warmer than the climate we observe at present in the Arctic and moderate latitudes, is much more characteristic of the Earth than the glacial climate of our time. We can easily check this by considering in detail the changes in the climate during the Cenozoic era which extends to the present.* The Cenozoic era is divided into two very unequal periods—the warm Tertiary which lasted about 70 million years, and the cold Quaternary (Glacial, Anthropogene), which extends into the present and has lasted, according to the estimates of various researchers from 500,000 to 800,000 years.

About 80 million years ago, somewhere between the Mesozoic and Cenozoic eras, the Earth was going through one of the most favourable climatic periods. Sometimes this is referred to as the Cretaceous Paleogene period. At that time the climate of subpolar latitudes resembled the modern subtropical climate. The Arctic islands and the Antarctica were covered with forests. The temperature of the surface waters of the Arctic Basin of the late Cretaceous period in the area of Alaska and Siberia was 14°C, although the temperature was only a little higher at the equator than in our time.

There is nothing surprising about this geographical paradox. Even in the present-day glacial conditions 53 per cent of the surface waters of the World Ocean have a temperature between 20 and 28°C and only 13 per cent have a temperature of 4°C or less, which would explain the mean temperature of 17.4°C. It must be remembered that during the late Cretaceous period the Arctic Basin had a more intensive water exchange with the equatorial basins than it has now (Fig. 2). Moreover, under the present-day cold conditions the Earth's heat losses are much greater than under warmer climatic conditions, because the ice fields which float on the World Ocean's surface, the ice shields which cover Greenland and the Antarctica, and the land regions which are covered with snow for several months in the year reflect solar radiation into space, and because the atmosphere contains less humidity at the lower temperature.

Lastly, the increased reflection of solar radiation from the deserts whose albedo is higher than that of any area covered in vegetation also deprives the Earth of heat.

During the Cretaceous-Paleogene period there were no deserts. They came into being at the end of the Neocene

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* Two hundred years ago the following names were adopted for the various geological eras: Primary, Secondary, Tertiary and Quaternary. The last two periods make up the Cenozoic, the most recent era of the geological history of the Earth. The Tertiary system is subdivided into the Paleogene (which is, in its turn, divided into the Paleocene, Eocene and Oligocene epochs) and the Neocene (which divides into the Miocene and Pliocene epochs).

period as a result of a considerable cooling in the high latitudes and the consequent general decrease in evaporation from the ocean surfaces. The most arid regions, smaller in area than the present-day deserts, were covered with a tropical savanna, with oases in river valleys.

The division into climatic zones, which is the result of the sharp temperature contrast between the poles and the equator was limited during that time, by the higher temperatures in the polar zones of both hemispheres. The same plants are found in the geological deposits in Greenland, Spitsbergen, the Bear Islands, North America, Western Europe, the USSR, Australia, the Antarctica and Africa.

But about 70 million years ago the greatest depression in the world climate began, and it culminated 20,000 years ago. During that time the Earth cooled continuously and increasingly. Fig. 3 shows how the temperatures dropped in the coldest month and, with it, the total annual rainfall in the areas of Kiev, Central Asia and Yakutsk, and how the mean annual temperature changed in Western Europe. The amazing correlation between the changes in temperatures and in rainfall shows the connection between them clearly.

Let us examine how the cold impoverished the vegetative cover in the northern latitudes as the world climate became increasingly depressed during the Tertiary period.

During the *Paleocene* era the water-lily, rose, poplar and birch grew in Grinnell Land, latitude 82°N; the chestnut, grapevine, ginkgo and oak grew in Greenland. Magnolias grew as far north as latitude 70°. The climate in the Volga areas was warm and humid, like Southeast China and Southern Japan today. Palms, ferns, evergreen oaks and laurels grew in the Volga areas. As in China and Japan today, the dense evergreen forests also included deciduous trees from the temperate zones like the beech, birch, oak, poplar and ash.

During the *Eocene* era subtropical coniferous and broad-leaved forests with holly, myrtle and palm grew on Spitsbergen, in the Far North, the European part of the USSR and in the Northern Urals, while the poplar, sequoia and pine trees grew in north Yakutia and on the New Siberian Islands. Palms grew as far north as the Cook Inlet in Alaska, latitude 62°; flora very similar to that of present-day South-

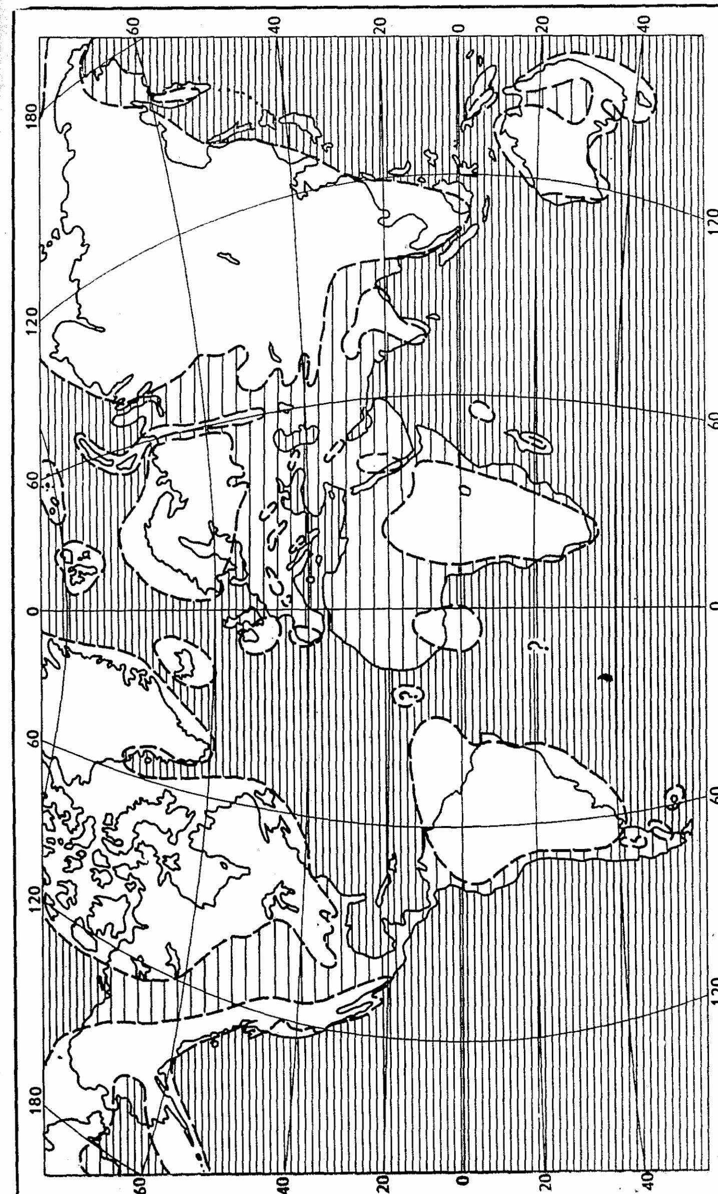


Fig. 2. Paleogeography of the Cretaceous period. Upper Cretaceous epoch (according to N. M. Strakhov, as cited by K. K. Markov, 1951). The land areas which were covered by sea are shaded

east Asia was widespread in the north of Canada, Greenland and Spain. The entire territory of the USSR except, possibly, the high mountains was covered with evergreen forests. Palms now growing in Indochina, Philippines and Indo-Malayan Archipelago were widespread in the Ukraine. But by the end of the Eocene it began to turn cold.

During the *Oligocene* the temperature of the subequatorial deep waters, which was 14°C at the end of the Mesozoic era,

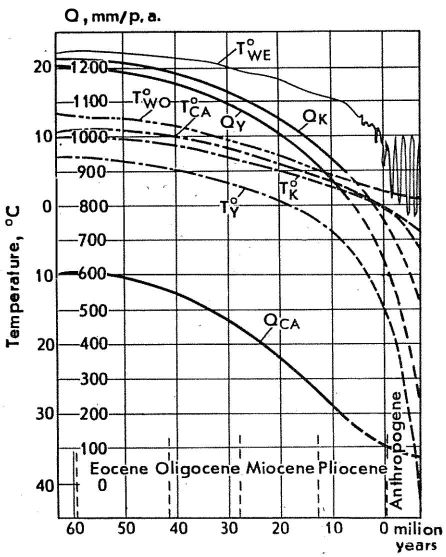


Fig. 3. Comparison of variations in temperature and precipitation during the Cenozoic era at different points in Eurasia. Temperature: T°_{WE} —West European mean (P. Woldstedt, 1954); T°_{WO} —World Ocean's bottom layer at the equator (C. Emiliani, 1954); T°_{CA}—the coldest month in Central Asia; T°_{K}—Kiev; T°_{Y}—Yakutsk. Precipitation: Q_{CA} —Central Asia; Q_{K} — Kiev; Q_{Y} — Yakutsk (V. M. Sinitsin, 1965). The Anthropogene's horizontal scale is magnified by about 10 times

dropped to 10.4 ± 0.5°C. The climate grew progressively colder over the whole planet. In the USSR the boundaries of the forest zones altered. Under the influence of the lower temperatures, the subtropical Paleogenic forests in the northeast, the coldest Eurasian region, receded southwestwards and deciduous forests took over spreading westwards, beyond the boundary of the Urals.

Europe cooled more slowly; as well as the flora typical of a moderate climate (poplar, filbert, hornbeam, beech, chestnut, grapevine, etc.), there were also tropical palms, bread-fruit trees, etc.

During the *Miocene* era the migration of the most moisture- and heat-loving plants from the northeastern regions of

Eurasia southwestwards to the warm Atlantic accelerated. Various studies have shown that during the first half of the Miocene era the forests of the Verkhoyansk-Kolyma area still included hemlock, cedars, cypresses and a rich assortment of amentaceous and broad-leaved plants—walnut, chestnut, linden and beech. Towards the end of the Miocene the composition of the forests became impoverished by losing the broad-leaved plants, cypresses and hemlock. Since sequoias and the bald cypress continued to grow on the New Siberian Islands, so there could not have been any drifting ice in the Arctic Basin at that time.

In Western Europe the Miocene flora resembled that of the present-day flora in the Atlantic states of the USA, and South China and Transcaucasia. A variety of laurels, the sequoia, bamboo, palms and arborescent ferns were growing in France.

During the first half of the Miocene era a warm and humid climate very similar to the humid, subtropical climate of Transcaucasia with an annual rainfall of more than 1,000 mm and a mean monthly winter temperature above zero prevailed in the Crimea. During the latter half, the climate changed to Mediterranean (humid during the six winter months). In the areas of Stavropol, the Lower Volga, Lower Don and the Southern Ukraine now forming part of the steppe zone, a rich variety of broad-leaved beech and oak forests with relicts of evergreen plants persisted until the beginning of the Upper Miocene era. The Sarmatian flora of the Southern Ukraine was very like the present-day vegetation of the moderate latitudes of China—chestnut, hornbeam, maple, walnut, beech, oak, laurel and other, mainly deciduous trees. The Sarmatian flora of Taganrog was richer than the present-day flora of Western Transcaucasia.

The flora and fauna of the Ukraine at the end of the Miocene period was also indicative of a warmer and more humid climate than the present. Fossils of the rhinoceros, antelope, giraffe, ostrich, etc., have been discovered in the southwest of the Ukraine. During the Miocene period there was as yet no steppe vegetation on the present-day southern Russian steppes.

During the *Pliocene* period the topography of the continents and, apparently, of the floor of the World Ocean took on its present-day outlines. During the Upper Pliocene the

temperature of the bottom waters at the equator dropped to 2.2°C. It now averages 1.75°C. But the mean temperature of the surface waters of the oceans was still quite high. Near Iceland it was 5° higher than today, while in the Arctic Basin it was close to the temperature of the waters of the seas of Northern Europe and the Pacific today, not that of the Arctic. It follows that at that time the Arctic Basin had no ice sheet either and the difference between the temperatures of the equator and the North Pole was about half as great as it is in our time. Despite the fact that during the Neocene era the climate grew progressively colder, towards the end of the Pliocene it was still quite mild. A rich savanna-type fauna, including a number of heat-loving animals, existed near the Black Sea. The ginkgo, zelkova and elm grew along the Amur. In Eastern Siberia the deciduous taiga was supplanted by coniferous forests. In Yakutia heat- and moisture-loving plants like the Brazil nut tree, persisted until at least the beginning of the Quaternary period.

During the Pliocene era forests still prevailed in the European part of the USSR to a greater extent than they do today, although they lost the subtropical species that had grown here and there in the deciduous forests of the Miocene. The discovery of hippopotamus fossils in the Upper Pliocene deposits of Western Europe indicates that the climate of that time was much warmer than it is today.

These examples illustrate the important proposition that with a largely identical topography of continents and similar shorelines of the World Ocean, in the absence of drifting ice in the Arctic Basin, the climate of Eurasia, including the USSR, was more favourable than it is today, the vegetation more diverse, the area of desert smaller and not so arid and the regions now subject to droughts were more moist. On the whole the biological productivity was much higher than in our time. The same was true of the North American continent.

The Tertiary period ended in the Pliocene. As we have observed, the cooling of the entire surface of the Earth proceeded with a degree of acceleration throughout this period. The polar latitudes cooled most, the equatorial, least. During the last stage of the Pliocene, the cooling had created a "cold background" and had reached a "critical

point" where a further, although negligible, drop in the temperature caused a glaciation of the surface of the Arctic Basin, and then a glaciation of the northern regions of the continents. A new period had begun in the geological history of the Earth. It was named Quaternary, by time, or Glacial, by type. Thinking about the appearance of man during this period, the Soviet geologist, Academician A. P. Pavlov suggested in 1922 a new name for it—Anthropogene.

CLIMATES OF THE RECENT PAST (500,000-20,000 YEARS AGO)

During each interstage, especially during each long interglacial period, the vegetative cover acquired more heat- and moisture-loving components. The flora and fauna became richer. The glacial epochs, however, and it is important to emphasise this, were accompanied not only by considerable cooling in the regions of glaciation, but also by very substantial aridity.

I. P. Gerasimov

During the Quaternary period (Anthropogene) the Earth experienced at least three or four glaciations. The Quaternary period is divided into two very unequal parts: the Pleistocene, the duration of which is estimated at 500,000 years, and the Holocene, 12,000 years. The last glaciation in Eurasia and North America culminated about 20,000 years ago, i.e., in the relatively recent geological past. During the Quaternary period the climate changed extremely sharply. Fig. 3 shows that the temperature curve of the Tertiary period is much more even than the feverish curve of the Anthropogene.

There is no need to deal with each of the Pleistocene epochs because of their basic similarity. We will therefore only examine the Dnieper Glaciation (the maximum glaciation), and the Mikulino Interglacial epoch, which is closest to our time.

The *Dnieper Glaciation* (Riss in Western Europe and Illinois in the USA) was the largest. At its height the European ice sheet covered London, Cracow, Kiev and Dniepropetrovsk and extended nearly to Volgograd, and, along the Dnieper almost reached latitude 48°N (Fig. 4). In North America the glacier covered the whole northern half of the continent, extended still further south along the Mississippi valley to latitude 37°N and ended 1,500 km from the tropical line. In Scandinavia the ice sheet was 3.5 km thick and in the Novaya Zemlya area, 4 km, and the North American ice sheet was almost the same.

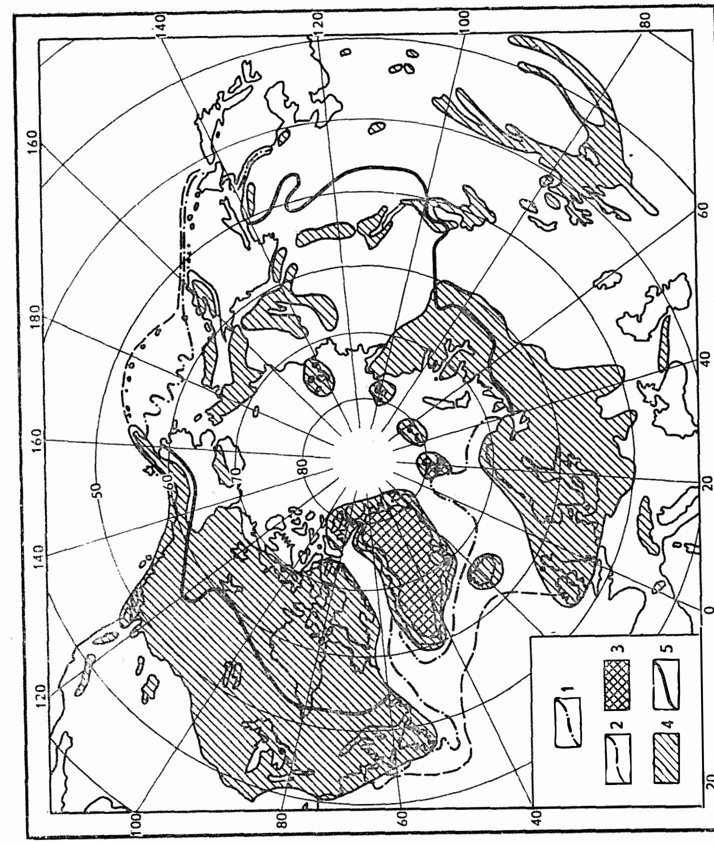


Fig. 4. The maximum spread of ice in the Northern Hemisphere during the Quaternary period. Mainland ice (surface and subterrain) and sea ice (K. K. Markov et al., 1968).
1—present boundary of sea ice;
2—ancient boundary of sea ice;
3—contemporary continental surface ice;
4 — ancient maximum surface glaciation;
5—present boundary of perennial ice and subterrain glaciation

The ice sheets of both the continents and the Arctic Basin were, because of their very high albedo, sources of additional stable cooling of the whole planet. They spread cold, dry air similar to the masses of Antarctic air which sometimes blows from the periphery of the ice sheet with hurricane speed. Tundras, deserts and semi-deserts developed extensively beyond the continental ice sheets. In Europe tundras covered the English Channel area, Paris, Luxemburg, Frankfurt and Leipzig, and thin forests with elements of the tundra, forest-tundra and xerophilous vegetation extended to the Mediterranean.

The *Mikulino Interglacial Period* (Riss-Würm in Western Europe and Sangamon in North America) lasted about 30,000 years and dates from between 100,000 and 70,000 years ago. It was a more favourable period than the later climatic optima. In Scandinavia the glaciers disappeared completely. At the height of the warm time the forests and vegetation of the lakes of Byelorussia were much richer than today. In the Crimea the steppe climate became more humid. Broad-leaved forests with beech, hornbeam, linden, yew and evergreen holly spread from the Balkans and Caucasus to the Russian Plain and reached the middle course of the Volga. The oak grew north of the Arctic Circle. The climate of Northeastern Europe was similar to the climate in Western Europe today. The glaciers even disappeared from the mountains of the Northeast of the USSR, where the climate was similar to the present-day climate in South Yakutia.

However, the climate of the Mikulino interglacial period as, incidentally, also that of any epoch in the Pleistocene, was not stable. This is shown by the series of moderately continental forests (pine, fir, birch) and the heat- and moisture-loving broad-leaved trees. On the whole, however, these fluctuations occurred under better heat and moisture conditions. The height of the Mikulino interglacial period was not only warmer, but also more humid than the Atlantic time of the Holocene in the more recent past.

The Mikulino interglacial period was followed by the last glaciation—Valdai (Würm). Repeated backward and forward shifts of the edge of the glacier caused by changes in the Earth's thermal conditions have been noted over the 50,000-year period from the beginning of the glaciation to its

culmination (20,000 years ago). It is mportant to note that this glaciation is divided into two periods. The first, the Lower Würm, was longer, but the drop in temperature was smaller. The second, the Main Würm, was shorter and colder. The Lower and Main Würms were separated by a long interval. A. I. Moskvitin, a Soviet geologist, considers this warming so significant that he refers to it as an interglacial epoch.

During the glacial epochs there was considerably increased planetary cooling, a reduction in the humidity of the continents, and the climate became more continental. The interglacial epochs, on the contrary, were characterised by the disappearance of ice sheets from the continents (except the Antarctic and Greenland) and from the surface of the Arctic Basin. During the interglacial epochs the thermal conditions of the Earth's surface became more favourable than they are today, the aridity and continental character decreased.

The Pleistocene, the time of the greatest aridity, manifested itself on the most arid territory of the USSR, i.e., the Soviet Central Asian Republics. Thus even during the Pliocene, i.e., before the onset of the low temperatures of the Pleistocene, the climate of the Karakum and Kyzylkum deserts was characterised by a higher total rainfall and a higher winter temperature (see Fig. 3). During the Quaternary period the climate grew more arid. The steppe was supplanted by a semi-desert, and modern-type sand deserts began to develop.

CLIMATES OF THE CLOSEST PAST (20,000-100 YEARS AGO)

> Towards the middle of the Middle Holocene broad-leaved trees became most widespread and abundant in the area of Moscow. It was the time of the "climatic optimum" of the Holocene. The climate was characterised not only by a higher temperature, but also by greater humidity.
>
> *M. I. Neustadt*

In the recent decades paleoclimatology has acquired two powerful methods of research—the spore-and-pollen analysis and the radiocarbon method of dating. The former makes it possible reliably to determine the composition and ecological conditions of the plant communities in past epochs, the latter—to date these epochs with moderate accuracy.

The use of the new means of research in layer-by-layer studies of the continental deposits of the last 20,000 years resulted in the discovery of an unusually broad and striking spectrum of climatic changes. These results are particularly valuable because they concern the period that is the closest to our own.

We must now consider the climatic changes in the following most important stages.

20,000 years ago 67 per cent of the area of all the continental glaciers of the Earth was concentrated in the Northern Hemisphere as against only 16 per cent in our days (Table 1). At that time the European ice sheet covered the whole of Scandinavia, Finland and the Baltic Sea, including the Skagerrak. Its southern edge covered Berlin and Plock (Poland) and extended to Orsha, Smolensk, Rzhev and the Rybinsk storage lake. The North American Glacier was still larger. It covered the entire northern part of the continent, its southern edge almost reached Cincinnati, Pittsburgh and New York.

In the last 20,000 years the area of all the continental glaciers in the Northern Hemisphere has decreased by 24.5

Table 1

Continental ice (million sq km)
(R. Flint, 1957)

	20,000-18,000 years ago	Today
North America (including Greenland)	17.0	2.1
Europe	4.9	0.1
Asia	4.9	0.1
Southern Hemisphere total	13.3	12.6

million sq km, i.e., 91 per cent. Of the remaining 2.3 million sq km the Greenland Glacier alone covers nearly 1.8 million sq km.

The volume of continental ice today is estimated at 24-27 million cu km. It has been calculated that the complete melting of this ice would raise the World Ocean level by 65-70 m. The volume of continental ice during maximum glaciation increased by 16 million cu km and lowered the ocean level by 45 m. Since the mass of Antarctic ice reacts to the changes in climate extremely slowly (see Table 1) we would be entitled to assume that the increase in ice went mainly to form the continental glaciers in the Northern Hemisphere. In accordance with this the mean thickness of the ice sheet was 650 m. The maximum thickness was about the same and in the same regions as during the Dnieper Glaciation. On the periphery, the thickness was down below a few dozen metres.

In the central area of glaciation the temperature of the ice was, as our calculations show, about minus 10°C, i.e., much higher than the temperature of the ice in Greenland, which is minus 28°C, or than in the Antarctica where it is minus 50-60°C.

The relatively high temperature of the ice in the central area was of considerable importance, since the warmer ice, naturally, reacted to changes in temperature quicker than the colder ice sheets of Greenland and the Antarctica.

The 45-m lowering of the World Ocean level which resulted from the increase in the volume of continental ice caused a large part of the continental shelves to become

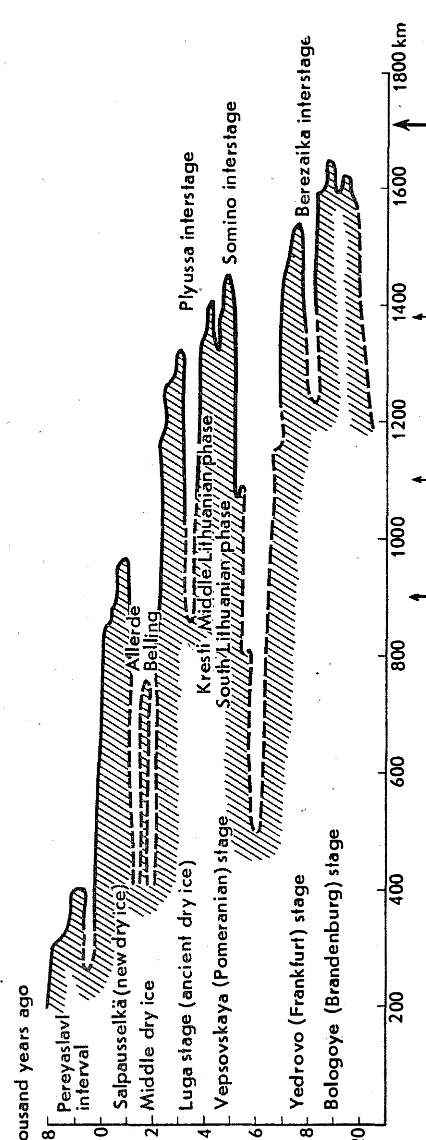


Fig. 5. Degradation of the Valdai glaciation in the Russian Plain (N. S. Chebotaryova et al., 1965)

dry. The Bering, Chirikov and Spanberg straits became so shallow that the water exchange between the Arctic Basin and the Pacific practically ceased, and, with it, the flow from the Pacific to the Arctic Basin.

The warming up and the consequent recession of the ice cover began 18,000 years ago. The recession was not steady. It was interrupted during the periods of lesser warming and by the invasion of the ice cover on territories which had been clear of ice (Fig. 5).

What were the reasons for such deep and relatively rapid changes in the continental ice sheets? It appears that quite insignificant, but stable changes in the heat balance of the surface layer of the ocean is enough to influence the natural processes considerably. This is evident from the example with sea ice. The British paleoclimatologist C. Brooks holds that a rise of only 1°C in the surface temperature of the Earth would be enough to make the entire ice sheet of the Arctic Basin unstable.

The thermal processes are especially effective on the borderline between the melting and freezing of water. The phase conversions (water, snow, ice) within one degree are accompanied by big changes in the absorption of solar radiation by the surface of the sea.

It has been calculated that, as a result of the melting of the sea ice, eight times as much heat is absorbed from solar radiation by the Arctic Basin as is necessary to reduce the thickness of the continental ice at the rate of 0.5 m a year.

During the last 18,000 years the warming was particularly appreciable during the Middle Holocene. This covered the time period of 9,000 to 2,500 years ago and culminated about 6,000 to 4,000 years ago, i.e., when the first pyramids were already being built in Egypt. It should be noted that the dating of the beginning of the culmination of warming varies: Gross dates it as about 7,500 years ago, the culmination lasting until 4,500 years ago, whereas, according to M. A. Lavrova, the culmination began about 6,000 years ago and was followed by a phase of the most abundant development of marine life, which lasted until 4,000 years ago (Fig. 6).

The most perturbing questions of the stage under consideration are: was the Arctic Basin iceless during the culmination of the optimum and what was in relation to this

the reaction of the climatic conditions on the continents?

Many scientists hold that during the climatic optimum the Arctic Basin was free of ice. C. Brooks substantiates his assertion by the fact that there was a relatively rich flora and no ice on Spitsbergen, there were warm water molluscs and the temperature of the open Arctic Basin and its coast was higher than it is today. At the same time a 2-2.5°C

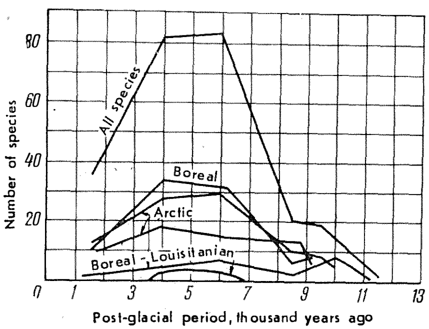


Fig. 6. Development of sea fauna in late and post-glacial sea deposits in the Kola Peninsula (M. A. Lavrova, 1960)

rise in temperature of the surface water and of the layer of air nearest the ground (which is quite enough completely to melt the drifting ice) has been very well demonstrated by a number of independently conducted studies using different methods.

The permafrost which covers the Arctic Basin greatly deteriorated during the period of its warming. Thus in the north and northwest of Siberia the melting reached a depth of 200-300 m. The mountain glaciers diminished considerably and in some places disappeared altogether.

How did the climate react to the disappearance of ice in the Arctic Basin?

The vegetative zones advanced towards the pole. On the Eurasian continent this latitudinal shift amounted to 4-5 degrees in the west and to 1-2 degrees in the east. Some plant species advanced their northern boundaries as much as 1,000 km. Forests extended right up to the Barents Coast and the oak, linden and filbert reached the shores of the White Sea. The information available warrants the assumption that on the European continent the tundra and forest-tundra zones disappeared completely. In the northern part

of Asia plant fossils were found only 80 km from Cape Chelyuskin and peat-moss was discovered on Novaya Zemlya. In the Ukraine, under favourable, more humid conditions than today, agriculture was developing for the first time. It has been established that the area of the Middle Dnieper was entirely covered by forest. Along river valleys forests descended to the Black, Azov and Caspian seas and broad-leaved trees were spread very densely from Saratov to the Lower Volga. The fact that the Tripolye and Lower Danube tribes cultivated all the main grain crops known today and bred cattle is also evidence of the favourable climatic conditions.

Many foreign researchers, including R. Capot-Rey and R. Fairbridge, agree that the hydrography and vegetation of Sahara show clear signs of an unstable climate. Lifeless wadis and dried-up lakes where, apparently, there was water only very recently are found in many places. The striking contrast between the ruins of ancient habitation in North Africa and the bare landscape surrounding it today denote a recent change in the moisture conditions.

It is interesting that during the Cenozoic era the Sahara desert reached the greatest aridity, and spread out precisely during the Quaternary period, i.e., at the time of the greatest planetary cooling, particularly the northern latitudes.

Even in late glacial time the upper reaches of the Nile received very little water from the Abyssinian Plateau because of the predominance of northeastern winds. The Nile did not reach the Mediterranean, as the Emba does not, in our days, reach the Caspian in seasons of drought. W. Fitzgerald asserted in 1942 that "the present hydrographic régime of North-East Africa was not inaugurated until the close of the last great glaciation of Northern Europe, probably about 12,000 B. C.", i.e., not before the disappearance of the main masses of ice in the northwestern part of Europe, the decrease in glaciation in the Arctic Ocean and the rise in the temperature of the surface waters of the North Atlantic.

From the 5th to the 3rd millennium B. C. inclusive the climate in the Sahara, the Arabian and Nubian deserts was much more humid. Man and animals were more widespread. The elephant, hippopotamus and rhinoceros disappeared in the Sahara at the end of the 3rd millennium B. C. The further

drying up of Sahara resulted in the departure of the nomadic tribes.

The well-known polar explorer, V. Y. Vize, established a connection between the decrease in Arctic glaciation and the rise in the level of African lakes, including Lake Victoria which is the source of the Nile. This connection is so stable that it has enabled the researcher to arrive at the very curious conclusion that by watching the level of the lakes one can estimate the ice conditions in the Arctic seas.

The absence of ice in the Arctic Basin during the culmination of the Middle Holocene optimum affected the climate of the whole planet favourably. All over Europe, from the Iberian Peninsula to the Volga, heat-loving forest vegetation prevailed. Man engaged in fishing and hunting, and the tilling of land was developing. In the mountains the forest line was higher than today. K. K. Markov wrote: "It should be emphasised that since the end of the glacial times there have been no signs of any systematic drying of the climate in Central and Northern Asia. Since the disappearance of the last ice sheet the climate on the Russian Plain is becoming generally more humid" (1956). And Y. P. Korovin noted that "the state of the vegetation of Central Asia during the epoch that followed the glaciation was characterised by a progressive development of mesophyllic-type vegetative formation. In connection with the recession of the glaciers, the general warming and humidification of the mountain climate, boreal flora which took shape in the middle latitudes of Siberia, soon after it was free of the surface glaciation, gained a foothold in Central Asia" (1958).

In Inner Alaska and the Yukon the absolute age of the peat deposits is estimated at 5,000 years. Hornwort has been found in deposits, 5,400-year-old, in Northeast Canada at a latitude of 64°19'N and longitude 102°04'W. Now hornwort only extends to latitude 59°14'N. On the eastern slope of the Rocky Mountains the age of peat found in the deposits of the last glaciation is 6170 ± 240 years. The climate in the basin of Lake Michigan was warmer and more humid 3,000 years ago than it is today.

The climatic changes in the San Rafael Lakes area (Southern Chile) during the late Pleistocene coincide chronologically with the fluctuations established in other areas in the Southern Hemisphere (Tierra del Fuego, Patagonia, Tristan

da Cunha, New Zealand). The climate in the Andes (latitude 39°S) during the interglacial stage was more humid than today; the main waves of the climatic changes were simultaneous in both hemispheres. The dry periods in Tierra del Fuego and Patagonia coincided with the boreal, subboreal and modern periods in Europe and the Kalahari Desert in Southwest Africa had a more humid climate 6,000-7,000 years ago than now.

The culmination of the climatic optimum of the Middle Holocene began to fade 4,000 years ago, and the ice sheet of the Arctic Basin began to reappear about 3,000 years ago.

According to M. I. Neustadt's division of the Holocene,

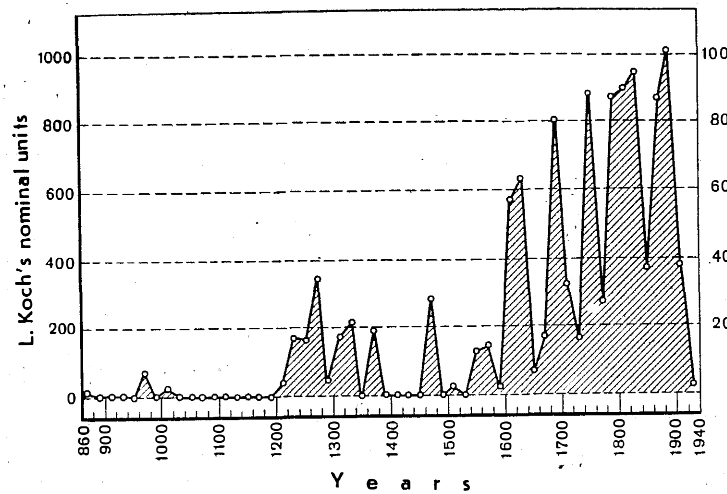


Fig. 7. Centennial fluctuations in glaciation from 860 A. D. to 1940 in the Atlantic area adjoining Iceland (L. Koch, 1945)

the Middle Holocene ended and the late Holocene began 2,500 years ago, more intensive cooling being recorded in the latter. However, about 1,000 years later, something after 500 A. D., a new warming began and, as Brooks has established, the Arctic ice entered the stage of semistable existence. This stage continued until about 1200 A. D. Brooks characterises the semistability of the Arctic ice as a complete disappearance in summer and a reappearance in a negligible volume in winter.

The floating ice in the Southern Hemisphere is in this state today; in the winter its area amounts to around 22 million sq km, while in February it decreases to 6 million sq km, i.e., by about 80 per cent. In the Arctic Ocean the total area of floating ice in the winter amounts to 11 million sq km, while in the summer, towards the end of melting, it may decrease to 7 million sq km, i.e., by one-third. If, however, we add to the balance of the floating ice in the Northern Hemisphere the ice in the Bering and Okhotsk seas which melts completely, and the quantity (up to) 20 per cent of the ice sheet in the Arctic Ocean, we shall see that there is 50 per cent smaller area of sea ice in the northern latitudes at the end of summer than at the end of winter.

According to the later data furnished by V. S. Nazarov, 37,000 cu km of sea ice freeze up and melt every year while 19,500 cu km of ice remain stable. In other words, 67 per cent of the sea ice on our planet is renewed every year. It follows that, if the sea ice is unstable at the present time, it was the more so during the early Middle Ages when the summer temperatures were 1-2°C higher.

L. Koch studied the dynamics of glaciation in the North Atlantic over the last 1,000 years. Its results are shown in Fig. 7. The low glaciation of the high latitudes reduced the force of the storms and the number of stormy days. The Asturian fishermen could engage in whale-fishing there in the 9-12th centuries.

Glaciation has also diminished in the Antarctic latitudes. As late as the middle of the 7th century A. D., the Polynesians sailed the Antarctic waters despite their primitive ships and navigation equipment. But, during the voyages of Captain Cook (1772-1775) the glaciation was much greater than today, to judge by his and his crew's descriptions.

The climate around Iceland and South Greenland was milder between 900 A. D. and 1200 A. D.; no sea ice was observed in this area. Norman colonies with an amazingly high level of cattle-breeding existed in Southwest Greenland. During excavations of a cemetery near Cape Farewell, now in the permafrost zone, archaeologists established that at the time of these burials the ground must have thawed in the summer because the coffins, cerements and even the corpses were pierced by the roots of plants. During an earlier period the ground must have thawed to a considerable depth because the oldest graves were comparatively deep. Later the lower levels became part of the permafrost zone and the later graves were shallower and shallower.

In the Alps the glaciers diminished considerably. According to Italian scientists, between the 8th and 13th centuries the climate was more favourable to farming than between the 13th and 15th centuries when droughts were more frequent. This also applies to the forest-steppe in southern Russia during the 9th and 10th centuries. Large, flourishing towns, ploughed land and nearly all known species of domestic cattle attest the high economic development of Kievan Russia.

In the 10th century Ibn Fadhlan observed that the Bulgarians who lived on the territory of the present-day Tatar ASSR had a well-developed agriculture and grew wheat. This is also confirmed by Russian chronicles. But it is well known that no wheat was planted in this area between the 14th and 19th centuries because of its rigorous climate.

Many historical and archaeological monuments indicate that there was enough water in Central Asia between the 8th and 12th centuries to engage in irrigation farming on nearly the whole area which lies between the Amu Darya and Syr Darya. According to Arab historians, a cat could have run over roof tops all the way from Samarkand to the Aral Sea. Not only the deserts of Central Asia, but also the world's greatest desert, the Sahara, was affected by the reduced glaciation of the Arctic Basin by some increase in humidity.

In the 13th century A. D. there was another cooling. It manifested itself the most completely between 1550 and 1850. During these 300 years rigorous winters were more frequent. Mountain glaciers became larger in Scandinavia, the Alps, Iceland and Alaska. In a number of areas they overran human habitation and cultivated land. According to P. A. Shumsky, during the 18th and 19th centuries the movement of the glaciers was in some places the greatest since the last ice age.

The pack ice that entered the Greenland and Norwegian seas from the Arctic Basin melted more slowly, so that enormous masses of ice blocked Greenland. The Norman colonies founded in the 10th century and flourishing until the

blockade began to lose contact with the home country, fell into decay, and by the middle of the 14th century, ceased to exist.

Despite some periods of warming and the consequent recession of the glaciers, the period under consideration was on the whole so cold that it has been called the Minor Ice Age. The high latitudes were frozen and the glaciation of the Arctic seas increased. During the postglacial period the sea ice in the North Atlantic attained its greatest development—for example, from 1806 to 1812 ships rarely managed to get beyond latitude 75°N.

The radiocarbon studies of the plant fossils taken from under 47 m of ice have shown that the glaciers of this area were advancing vigorously less than 200 years ago. During the culmination of cooling, the snow line dropped to the sea level, which, naturally, created favourable conditions for the renewal of the ice sheet which had disappeared during the preceding warm period.

During the drift of the *Fram* (1893-1896) the conditions for the formation of a thicker ice sheet were more favourable than today. Arctic explorers in the past often reported 4-6-m thick "paleocrystalline" floating ice, a rare event in our time because it is a product of a colder climate.

Intensive glaciation of the Arctic Basin has always engendered a disturbing atmospheric régime with noticeably more frequent years of famines.

MODERN WARMING OF THE ARCTIC (100 YEARS AGO—OUR TIME)

> In a mere 15 years or less there has been such a change in the distribution of the marine fauna as is usually associated with long geological periods.
>
> *N. M. Knipovich*

A hundred years ago, in the second half of last century, a new period of warming of the climate began. At first it was slight, even negligible, then gradually it became more intensive, and reached its culmination in the 1930s. The warming all over the Earth averaged 0.6°C. It was not uniform, being the greatest in the Atlantic sector of the Arctic and the least intensive in the Pacific sector (Fig. 8).

The ice sheet in the Arctic became smaller and thinner.

From 1893 to 1896 the Norwegian ship *Fram* drifted, locked in ice 3.56 m thick, while the Soviet *Georgi Sedov* (1938-1940) was sealed in ice 2.18 m thick, although she was somewhat farther north than the *Fram*. The total area of the ice had decreased by 1 million sq km. In other words, the mass of floating ice in the Arctic Basin decreased by around 50 per cent in about 40 years during which there were, of course, also uncharacteristically cold years.

Owing to an increased circulation of the atmosphere and ocean waters, the ice was carried out of the Arctic Basin into the Atlantic much faster. *Geogri Sedov* drifted from east to west twice as fast as the *Fram*.

The very appearance of the Arctic Basin had changed. The icescape now looked different and the ice sheet melted completely more often. In the summer more unfrozen patches appeared amid the floating ice, however thick and hummocky it may have been. The "Arctic Cake" was a mosaic of patches of pack ice, younger ice and of clear water. The littoral "paleocrystalline" ice which had been up to 6 m thick had almost completely disappeared.

After 1920 the Yugorsky Shar Strait froze two months later than usual and Saint Michael Bay, to the north of the mouth of the Yukon River, one month later.

The Greenland Sea was navigable for a considerably longer time. In the 1900s coal from West Spitsbergen could be shipped only over a period of three months, whereas in

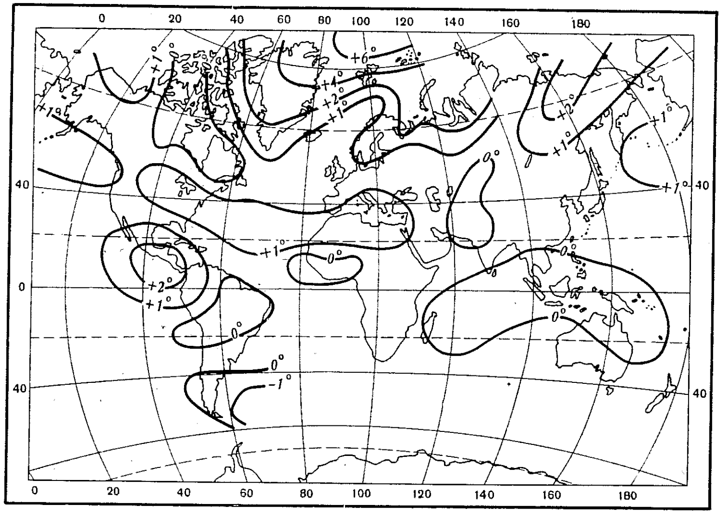


Fig. 8. Variations of mean annual temperatures (°F) from 1920 to 1940 (H. C. Willet, 1953)

the 1940s it could already be shipped for seven months, and the sea around Spitsbergen was navigable for a period of nine months.

In 1901 the icebreaker *Yermak* could not get to Cape Zhelaniya, whereas in 1935 the *Sadko* sailed in clear water to the northern tip of Severnaya Zemlya and thence 1,000 km northeast, reaching latitude 84°41′N. In 1938 the *Yermak* set up a record in Arctic navigation getting to within 700 km of the pole in the New Siberian Islands area.

The waters also grew warmer in the North Atlantic and the North Pacific, and presently fish began to drift to the high latitudes. In 1908 and 1909 cod fish was caught in appreciable quantities only at the southernmost tip of Greenland, whereas in 1920-1930 it began to be caught also near

Spitsbergen. Herring, sardines, grey mullet and other fish also drifted northwards.

The rise in the air temperature was particularly noticeable in the high latitudes, especially in winter. In the 40 odd years that had elapsed between the journeys of the *Fram* and *Georgi Sedov* the mean annual temperature had risen 3.9°C, the December temperature, 9.4°C, while the summer temperature changed hardly at all.

Despite its short duration the warming also affected the Southern Hemisphere. The iceberg zone in the Antarctic seas decreased in radius by about 1,200 km, and some shelf glaciers were destroyed. The edge of the ice sheet receded in some places in the last 50 years, even if only a little. In the tropical latitudes this warming was very slight. But the humidity in the areas of latitude 50°N was appreciably affected. In Berlin, Leningrad, Arkhangelsk, Moscow, Kiev, Sverdlovsk and Irkutsk there was more rainfall than the mean perennial norm (Y. S. Rubinshtein, 1946). With the decrease in the glaciation of the Barents Sea a certain increase in the humidity was noted in Central Asia. The same relationship was found in the Ukraine and the Volga areas. It was also noted that with the warming of the Arctic the level of the lakes rose somewhat in Western Siberia, Kazakhstan, the Caucasus, Iran, Asia Minor, Pakistan and Central Asia. According to foreign researchers, the amount of rainfall increased on Spitsbergen, in Britain, Spain, France, Switzerland, West Germany, Japan, Central Mexico, Ceylon, Australia, etc.

In a word, both heat and moisture increased on the continent, and it is only natural that the animal and vegetable kingdoms benefited from this increase.

As has already been stated, the overcooled Arctic always has an adverse effect on the crops, whereas during the warming, when the volume of floating ice in the Arctic noticeably diminished, there were also fewer years of drought. In 36 years (1922-1957) there were 14 drought years in the south of the European part of the USSR, i.e., one-third less than during the preceding 33 years (1889-1921).

In Western Siberia droughts are usually preceded by particularly cold winters. The soil cools a great deal and freezes deeply, which decreases the penetration of melted snow into the soil during the spring thaw. In the beginning it

looks as though there is a lot of water because a good deal of it runs off the fields. But that is just it: it runs off. The frozen soil is impervious, does not retain it, and the water runs off uselessly.

It should be noted that at the end of the 18th century there were five drought years almost on top of each other. It transpired that these years had been the coldest (in what

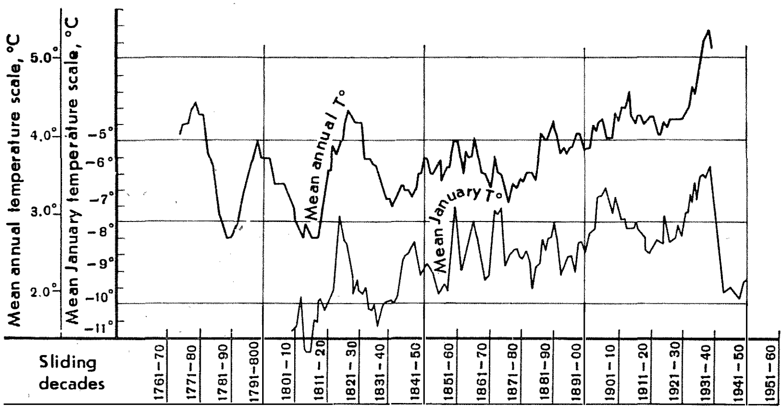


Fig. 9. Centennial mean annual and mean January temperatures in Leningrad

is now Leningrad) in the almost 200-year period of instrumental observations (Fig. 9). The drought years in the 19th century also coincided with low temperatures (as recorded in the Leningrad area).

With the warming of the Arctic the flora reacted to the call of the warmth and the northern boundaries of the vegetative zones began to shift towards the pole. Thus on the territory of the Bolshaya Zemlya Tundra the northern boundary of the forest spread northwards at a rate of 0.5-0.7 km a year, whereas in the 1830s and 1840s these same forests had shown clear signs of deterioration. The forests were also observed to spread northwards in Scandinavia, on the West Siberian Plain, in Alaska and on Labrador. In a number of regions many species of plants and animals spread 200 km and more towards the pole. Birds began to nest on the

Yenisei and the Lena, although formerly they had only nested to the south of the present areas.

The climatic conditions also improved in the southern areas of the USSR. The summers grew warmer in the Buryat ASSR and the ice became thinner on Lake Baikal. In Northern Mongolia, where the forests are at the southern fringe of their distribution, larch and pine forests were quickly restored. Young forests were observed to advance into the steppe. Heterophyllous poplars and Gobi elms began to grow in the Gobi Desert again. During the height of the warming of the Arctic cotton began to yield richer crops in Uzbekistan.

The areas under crops expanded and the grain crops increased in other countries. In Canada the farming boundary moved 100-200 km north. Vegetables began to be grown, owing to the warming, in Sweden, Norway and Finland, although formerly this had seemed impossible in their climate. In the mountain areas of Italy the beech spread to higher altitudes. More migratory birds appeared in Iceland and Greenland, while in Europe polecats and hares reacted to the warmth by expanding their domain 600-700 km northwards.

Transport became more active and the period of navigation increased by 17 days on the Western Dvina and by three weeks on the Neva. Near Yakutsk the ice in the Lena began to break four days earlier than usual.

Thick layers of perennially frozen ground began to melt. The melting was clearly observed in the area of the North Urals, the basins of the Lena and Yana, and in other areas, and it need hardly be said how important this is for construction and industry.

A recession of the continental ice was noted everywhere in both hemispheres. In the Swiss Alps the glaciation area shrank by 25 per cent in 50 years (1890-1940). The glaciers in Iceland, Sweden and Norway receded and even those near the equator—on the peaks of the Kilimanjaro, Ruwenzori and other mounts—became smaller. In Greenland the ice sheet receded to such an extent in some places that it uncovered the land of the 12th century Norman colonies. In Iceland the ice receded from the land that had been cultivated 600 years previously. The picture on the Scandinavian Peninsula was similar. A rise in the snow line was noted all over the

world. For example, it rose 900 m in the mountains of Peru.

During the most intensive warming some people thought that before very long the Arctic Basin would be completely free of floating ice. But ... in the winter of 1939-1940 a slow cooling began again. During the 30 odd years that followed the temperature all over the Earth surface dropped an average of 0.3°C. There was an increase in glaciation in the Arctic Basin and in the size of mountain glaciers.

Thus during the Cenozoic era the climate on the Earth gradually deteriorated. A most important parallel is very clearly revealed, namely, that the ecological conditions, i.e., the conditions of habitation for the plants and animals, deteriorate at all latitudes, from the polar to the tropical, under a régime of falling temperature on the Earth surface. At this point it must be emphasised that the greatest cooling in the last 200 million years, and possibly in the entire geological history of the Earth, occurred only between 18,000 and 20,000 years ago, during the last stage of the so-called Valdai (Würm) Glaciation. The amazing proximity of the large and in some cases even maximum fluctuations of the climate to our days will help in revealing their causes and laws in the past.

CAUSES OF THE CHANGES IN CLIMATE

> It is necessary first of all to analyse the change in the geographical peculiarities of the Earth surface rather than hasten to resort to astronomic and cosmic hypotheses.
>
> *K. K. Markov*

In 1841 J. L. R. Agassiz, a Swiss naturalist, voiced the bold opinion that at one time Scotland had been covered by a heavy layer of ice. This opinion was received with scorn and it took 20 more years for the hypothesis to be confirmed. For more than 100 years scientists have been persistently seeking the causes which could have had an influence on the formation and transformation of Earth's climate. The range of conjecture was enormous—from cosmic catastrophes to a cigarette dropped in the Siberian or Canadian forests. Yes, a cigarette! A cigarette set the forest on fire. The clouds of smoke from the spreading fire could have reduced the flow of solar radiation to the Earth surface, including the surface of the Arctic Basin. Failing to get enough heat from the sun, the surface layer would lose heat and the temperature would drop; this would be followed by freezing and, lastly, through the self-cooling and self-growing (we shall deal with this mechanism below) it would lead to the glaciation of the continents.

Some researchers look for the causes of climatic fluctuations outside the Earth, and regard cosmic conditions as of paramount importance. They connect the climatic changes with changes in the Earth's rotation, including a shift of the rotation axis inside the planet, and the variations in the angle of inclination of the Earth rotation axis in relation to the plane of the ecliptic; others—with changes in the outlines of the continents and oceans, in the relief of the land and the ocean floor, in the composition of the atmosphere, solar radiation, etc. But very few of the researchers check on

the plausibility of their own hypotheses with measurements and calculations. Of course, in some cases each of the hypotheses has a modicum of probability and plausibility. But not one of them could explain the concrete diversity of the climatic changes observed during Cenozoic history of our planet: protracted drop in temperature over scores of millions of years, as in the beginning of the Cenozoic era, alternating with amazingly frequent, almost feverish changes in the climate, when in the course of one or two millennia or even only a few centuries the winter temperature in the Arctic latitudes leapt dozens of degrees, as at the end of the Quaternary period.

The latest studies have shown that during the last stages of the Quaternary period the changes in climate were particularly frequent. The theory of a single glaciation—monoglacialism—which formerly had quite a few adherents has now been abandoned. Until the beginning of the 20th century it was held that after the disappearance of the last glacier the climate remained stable, and it was only established in 1910 that there had been a considerable and protracted climatic change during the Middle Holocene; it was so significant that this can be compared with an interglacial stage. Isotopic methods enabled the American scientist C. Emiliani to establish in 1955 that there were fifteen major changes in climate during the Quaternary period. Recent years have furnished new evidence of considerable warmings and coolings in the last 100,000 years which had been unknown previously.

These discoveries have deprived the former cosmic, astronomic, tectonic and other hypotheses of conviction, although it cannot be denied that each of the factors in these hypotheses quite possibly, under certain conditions and at certain times, influenced the changes in climate. At any rate these hypotheses cannot explain the surprisingly rapid and differently directed transformations of the planetary climate in the last 20,000 years, to say nothing of the more numerous fluctuations during the Anthropogene.

The scientists are therefore still looking for and studying the mechanisms that may control the changes in the climate. The most diverse data is being used from geology, paleogeography, geophysics, paleontology, archaeology, ancient and medieval history, and many other sources. Round-the-

clock instrumental observations of the natural processes in the atmosphere and the World Ocean have been thoroughly conducted for many years. Of late Soviet and American scientists have made extensive use of satellites, with their many automatic devices, for this purpose. Today the satellites ensure uninterrupted and broad observations. They systematically transmit vast amounts of information on many changing situations, such as thermal contrasts, the snow cover, sea ice, baric formations, cloud structure, sea currents, the state of the vegetative covers and a great deal more. The scientists are united in large international collectives, like those formed during the International Geophysical Year, the International Geophysical Co-operation and other international research organisations.

The extensive information now available makes it possible to explain the changes in climate from the beginning of the Cretaceous-Paleogenic optimum to the most recent fluctuations in our time without involving extra-terrestrial factors, but only by the action of two mechanisms inherent in the atmosphere and hydrosphere of the Earth and in the state of its surface. One of these mechanisms caused and is still causing a slow, gradual depression of the planetary climate all through the Cenozoic era, and this depression also accounted for the drop in the temperature of the deep waters of the World Ocean. The other mechanism, by superimposing itself on the former, determined the frequent fluctuations which occurred during the Quaternary period.

Let us trace the cooling of the Earth since the Tertiary period, that is, for about the last 70 million years.

To do this we have to descend to the floor of the World Ocean. The ocean floor heats the waters that cover it—it does not cool them. Nevertheless, the deep waters did cool during this period; the cold came from the surface and not from the bottom. Sinking to the floor the surface waters brought the cold with them, the cold neutralised the warm current which came up from the floor, and formed deep, cold layers.

But how is the cold transferred from the surface to the bottom?

It is well known that when it drops in temperature fresh water increases in density, but only down to 4°C. A further drop in the temperature of water will cause the density to

decrease again. In other words, fresh water is at its densest at 4°C. On the surface of a reservoir it may freeze, as it should, at 0°C, but at lower levels it will retain a temperature of +4°C.

It is different with sea water. The density of sea water always increases with the increase in salt content, and the freezing point drops. Fresh water freezes at 0°C, salt water with an average salt content of 35 per mill (35 g of salt per 1 kg of water) will freeze at minus 1.91°C. Surface waters, therefore, are capable of cooling the deep ocean waters to almost minus 2°C.

Table 2 gives some idea of how the deep waters cooled in the last 75 million years.

Table 2

Temperature of the bottom waters of the World Ocean in the distant and recent past

Epoch	Approximate age (million years)	Temperature (±0.5) °C	Approximate rate of cooling in 10 million years, °C
Upper Cretaceous	75	14.0	0.9
Middle Oligocene	35	10.4	1.7
Lower and Middle Miocene	15	7.0	3.4
Upper Pliocene	1	2.2	4.0
Modern	0	1.8	

It has been demonstrated by a number of studies that during the Cenozoic era all the continents and the axis of the Earth's rotation were in the same position as now. It follows that the modern polar latitudes were then also the coldest. But the Antarctic was, as it still is today, colder than the Arctic because the centre of the Antarctic is occupied by a large continent, Antarctica, while in the centre of the Arctic is the large Arctic Basin which had a good water exchange and, consequently, heat exchange with the warm tropical basins (see Fig. 2). That is why during the Cretaceous-Paleogenic optimum the vegetable kingdom of the Arctic latitudes was much richer and more heat-loving than in the Antarctic latitudes.

During the Upper Cretaceous epoch (about 75 million years ago) the temperature of the Arctic Basin surface waters was the same as the deep waters at the equator, i.e., 14°C. So these deep waters must have been cooled by the Antarctic waters. That this was so was also shown by the recent studies of the bottom deposits in the Antarctic. The sediments engendered by icebergs are of such ancient origin that the Arctic has no blame at all since at that time the Arctic had no ice sheet. It had no part in the cooling at all. The ice could only have existed in Antarctica. Moreover, the beginning of Antarctic glaciation dates from the Eocene (about 60 million years ago). At any rate a cooling was observed as far back as the Cretaceous period. Geological findings show that from the Cretaceuos period to the last stage of the Cenozoic era the land rose more than it sank with the result that the continental territories were larger. Although the advance of the sea at that time was superseded by recessions which were, in their turn, superseded by new advances, these were never as extensive as the preceding recessions. The rise and increase in the continents gradually reduced the water exchange between the polar and equatorial waters and the ocean's heat exchange which resulted in an increasing thermal insulation of the polar latitudes.

Together with the rise of Antarctica in relation to the warm waters of the Southern Ocean which surrounded it, the winter snowfall also increased. Gradually there was an accumulation of unthawed snow. When this eventually reached the critical stage, the process became irreversible, and the continent was buried under a coating of ice. This snow coat reflected the solar radiation almost completely which caused enormous heat losses. The layer of air next to the ice was cool and dry. It became more transparent to infrared radiation from the Earth surface. The heat balance became negative and self-cooling set in.

One trouble led to another. The more the Antarctic ice sheet grew, the worse the radiation conditions became; the worse the radiation conditions became, the more the ice sheet grew. The cold engendered by the Antarctic began to spread all over the globe. The ocean waters surrounding the Antarctic cooled. With the drop in temperature the waters grew denser; the denser the waters, the more ran down the continental slope. The accumulation of cold bottom waters

began to spread to the north, cooling the deep waters of the World Ocean at all latitudes.

Presently the Arctic also helped to accelerate the cooling of the Earth surface and the deep waters. This is shown by paleogeographic and geological data. Owing to the predominance of the continental rise over the continental sinking during the Eocene the straits through the North American continent dried up and so reduced the passage of heat to the North Pole. A still greater reduction occurred during Oligocene when the West Siberian Strait connecting the Arctic Basin with the warm Indian Ocean dried up (see Fig. 2). Along with the cooling of the Arctic Basin the Earth atmosphere also cooled. In the Northern Hemisphere the heat boundaries began to shift southwards.

The consolidation of the continents towards the present-day outlines of the World Ocean occurred during the Miocene. These "innovations" were unfavourable to the water exchange of the Arctic Basin. Its connection with the southern basins decreased still further and was accompanied by greater cooling. From being a victim, the Arctic Basin became a culprit. It caused the cooling of the air masses passing over it, and began to feed the World Ocean with cold water. Greenland also came into play. It became glaciated and also turned into a source of cold. However, Antarctica still played the main role in cooling the surface of the Earth.

The climatic deterioration accelerated. The rate doubled. Whereas in the beginning it had taken 40 million years for the temperature of the deep waters to drop 3.6°C, there was a further drop of 3.4°C in only 20 million years.

It has been said that the climates during the Miocene only differed from today's climate because the continents had a different shape. It must be emphasised that it was during the Miocene that the shores of the World Ocean and the continents took on their present-day configuration, so that subsequent transformations in climate cannot be explained by changes in the outlines of the continents.

During the *Pliocene* the configuration of the World Ocean did not essentially change. However, land continued to rise above sea level faster than it went down into the sea. The relief of the continents changed, and the relief of the ocean floor may also have changed.

The increase in the height of the land was accompanied by further cooling of the Earth surface. It noticeably increased on the ground which was much higher than the lower boundary of the chionosphere. This gave rise to new mountain glaciation centres which fostered a general increase in the snow and glaciers which further encouraged the general cooling.

During the Upper Pliocene the temperature of the bottom waters at the equator dropped to 2.2°C. Compared with the preceding Oligocene-Miocene interval the rate of cooling during the Miocene-Pliocene period once again doubled. Towards the end of the Pliocene the temperatures of the layer of air near the ground and the temperature of the deep waters no longer dropped at the same rate. The air temperature dropped faster, because of the greater thermal inertia of the deep waters and the certain momentum of the air masses. This difference increased as the rate of cooling increased, particularly as the temperature of the surface waters of the polar basins approached their freezing point.

The upper curve in Fig. 3 shows that at the end of the Pliocene the drop in temperature was not continuous. It was interrupted by warmer spells. This warrants the assumption that a second mechanism, capable of producing different changes in the temperature of the ground layer of the atmosphere and, consequently, in the climate, was at work alongside the first which had been causing the slow, continuous cooling since the beginning of the Cenozoic. The effects of this second mechanism were clearly manifested during the *Quaternary period*.

What was this mechanism?

It is well known that, in its liquid state, water absorbs the heat of solar radiation fairly well, whereas ice and snow, contrariwise, reflect, and, as it were, reject its heat. It follows that whether the sea surface collects heat or emits cold will depend on whether it is liquid or frozen. Let us imagine the scores of millions of square kilometers of sea surface on our globe which can melt or freeze and we shall see the significance of this powerful planetary climatic factor.

Since it only takes a slight change in temperature for the water to freeze or melt, a small shift up or down the critical point (0°C for fresh water and minus 1.9°C for salt sea

water) will give us either a liquid (water) or a solid (ice). That is why the slight but protracted disturbances in the transfer of heat in the hydrosphere or the atmosphere can and did cause quite disproportionately large changes in the thermal régime on the Earth surface.

C. Brooks, a British scientist, has calculated how deeply the surface of the Arctic Basin would cool if it were completely covered with ice. Let us imagine the Arctic Basin free

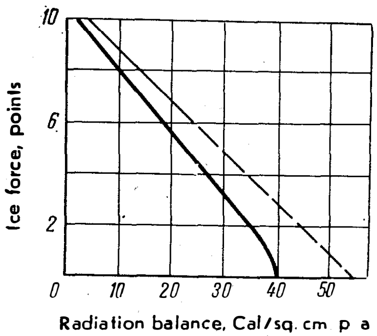


Fig. 10. Dependence of the radiation balance on the glaciation of sea surface in the Central Arctic Basin
— according to V. L. Gayevsky;
— — extrapolation;
— used for calculations

of ice and that the temperature of its surface waters approaches its freezing point only during the coldest month. In this case a slight initial cooling of only a fraction of a degree would suffice to engender an ice sheet which could lead to a further 28°C drop in temperature. And all this could happen without the help of any extraneous influences. Under normal conditions, 0.1-0.3 of a degree is hardly perceptible, but in the fatal neighbourhood of the critical point it can have a tremendous effect. Brooks writes: "This result greatly simplifies the problem presented by warm polar climates. Instead of having to account for changes in temperature of the order of 50°F we have only to account for initial changes of 5°F or so, since we can safely leave the floating ice to make up for the odd 45°F" (C. Brooks, 1950).

The ice sheet cools the air immediately above it to the same —28°C, the cold and denser air spreads beyond the edge of the ice where it encounters open water, cools it and the water freezes. This becomes a chain reaction. Contrariwise, when the heat advection in the Arctic Basin increases the temperature, the chain reaction is reversed. The big temperature evolution during the Anthropogene took place possibly

precisely because the succession of phases (ice phase, water phase) in the surface layer of the ocean can engender such large changes in the heat balance. A reduction in the size of the ice sheet increases the power of solar radiation. In the polar latitudes the albedo of the surface may change from 90 per cent and more (ice and snow) to 9 per cent and less (water). A tenfold drop in the albedo increases the radiation balance in the Arctic Basin from 4 Cal/sq cm a year under the modern conditions of 10-point ice to 50 Cal/sq cm a year in the total absence of ice (Table 3 and Fig. 10).

The table shows a rapid increase in the radiation balance. To each point of decrease in glaciation the balance responds with an increase in 5 Cal/sq cm a year (average).

It is not hard to calculate that with such a variability in the radiation balance the melting of the sea ice in the Northern Hemisphere would produce an increase in heat of about 5×10^{18} Cal/year.

If one takes into account the possibility of melting the sea ice in the Southern Hemisphere and reducing the area and duration of snow cover on the continents, the thermal balance of the Earth surface would produce the whole increase by more than 10^{19} Cal/year. This volume of heat is equivalent to 14,000 trillion tons of coal with a normal efficiency of 7,000 Cal/kg.

What does this all signify?

When the Earth cooled to a point where the surface of the Arctic Basin froze, as was the case at the juncture of the Pliocene and the Pleistocene, slight but stable changes in the planetary circulation of the atmosphere and hydrosphere sufficed for either an ice sheet to develop in the polar and partly moderate latitudes or for these latitudes to become warmer than they are in our time.

The point in this wide amplitude—from glaciation to a total absence of ice in the northern latitudes—at which the Earth finds itself, depends on the degree of variability of atmospheric processes and on disturbances in the circulation of the hydrosphere which are connected with them. According to the latest concept these changes in the planetary circulation of the atmosphere are conditioned by fluctuations of solar activity.

The mechanism that connects these fluctuations with the changes in glaciation is well illustrated in Fig. 11 which

shows that the increase in solar activity increases the frequency of the meridional types of atmospheric circulation which, in their turn increase the inflow of warm Atlantic waters to high latitudes. The increase in sea and air advection raises the temperature of the Barents Sea and, incidentally, also that of the entire Atlantic part of the Arctic Basin, which, in the end, leads to a decrease in the total glaciation including the drift ice.

Table 3

Changes in the components of the radiation balance depending on glaciation, Cal/sq cm/year (V. L. Gayevsky, 1959)

Components	Glaciation, points				
	10	9	8	7	6
Absorbed radiation	21	25	30	34	39
Effective radiation:					
during polar day	—6	—6	—6	—6	—6
during polar night	—11	—11	—10	—9	—9
Radiation balance:					
during polar day	15	19	24	28	33
during polar night	—11	—11	—10	—9	—9
Mean annual radiation balance	4	8	14	19	24

The same connection between the centennial changes in solar radiation and glaciation of the Atlantic sector of the Arctic through the circulation of the atmosphere and hydrosphere had been established somewhat earlier by I. V. Maksimov and was shown again by L. G. Polozova.

These interrelations of the heliogeophysical phenomena warrant an extrapolation of the more protracted and deeper changes in the past, as the laws which determined the climatic fluctuations during the first half of our century had to operate during the entire Anthropogene. It must therefore be recognised that the reasons for the frequent and large-scale climatic changes during the Quaternary period were links in a long chain. It begins in the activity of the Sun and includes the physico-geographical peculiarities of the Earth surface, primarily, as we have seen, in the changes in oceanic advection and the character of inter-oceanic water exchange.

The latter needs to be dealt with in greater detail. When the changes in climate are considered, two of the main components—heat and moisture—which depend on the character of the water exchange between the Arctic Basin and more southern basins of the World Ocean are usually analysed. The water exchange with the North Atlantic is the most

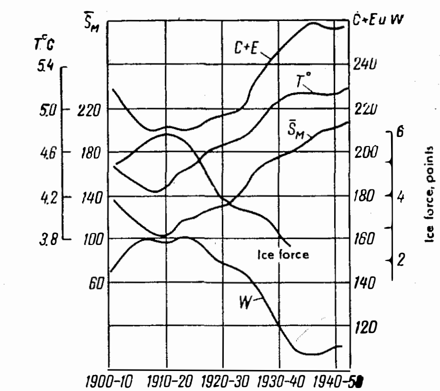


Fig. 11. Comparison of perennial variations in the solar activity (according to index $\bar{S}_M$ of the sun's Northern Hemisphere), the annual recurrence of meridional (C+E) and western (W) circulation, the annual navigational glaciation of the Barents Sea (May-August), and the mean temperature of the 0-50 m water layer in the cross-section of the Kola meridian in 11-year sliding averages (N. I. Tyabin, 1960)

effective. However, as the warm water is driven into the Arctic Basin which had only one open end, the climatic effect of the water exchange is not uniform along the northern coast of Eurasia, favouring the Atlantic rather than the Pacific sector. That is why the northwestern part of Eurasia is better off for heat than the northeastern part. This disparity prevailed all through the Cenozoic era, especially beginning with the Oligocene, when the land rose, separating the Arctic Basin from the Volga Sea through which the water exchange with the Indian Ocean was effected. Western and Northern Siberia were then better heated by the warmth brought by the Atlantic water than they had been during the Miocene.

The same trend can be seen for moisture as for heat. Moisture conditions were more favourable in the northwestern part. Since the main supply of both comes to the Eurasian continent from the Atlantic Ocean the moisture decreases along the latitudes from west to east as well. The dependence of moisture on heat supply can be clearly seen in the west-to-east movement of air masses in moderate lati-

tudes. The drop in winter temperature eastwards from the Atlantic reduces the rainfall in Siberia.

When it grew warmer in the Arctic and the temperature contrast between the pole and the equator decreased the humidity in Eurasia increased.

I. P. Gerasimov and K. K. Markov wrote: "The warming during the interglacial and the postglacial epochs was particularly substantial in the Arctic. The horizontal temperature gradient (north to south) decreased. The comparatively warm and, therefore, moist masses of polar and Arctic air did not cause drought on their slow way southwards in the middle latitudes as can be observed today.... During the interglacial period the waters of the Barents Sea were so warm that the masses of air engendered over (or to the north of) them, held sufficient moisture" (1939).

Many years later (in 1956), K. K. Markov noted that after the disappearance of the last ice sheet from the Russian Plain the climate became generally more humid.

At this point it is necessary to emphasise the following factor. During the interglacial epochs the temperature of the surface waters of the oceans rose, evaporation increased, the temperature of the air rose, its moisture content increased and, with it, the rainfall on the continents.* O. A. Drozdov has established just how much the increase in rainfall depends on the increase in the moisture content of the atmosphere. For example, with an increase from 40 per cent to 80-100 per cent the ratio increases tenfold, but, what is very important, the most rapid changes occur in the interval of the mean relative humidity of 45-55 per cent in which the rainfall gradient increases 4.5 times. And it should also be noted that with an increase in heat and moisture supply, local evaporation on the continents, which in its turn stimulates rainfall, also increases. In a word, as it is often seen in life, one good thing creates another and it is high time we formulated the main laws of the climatic changes of the Quaternary period, which control our climate today.

* Thus, according to H. Flohn (1953), during the glacial epochs the evaporation from the surface of the oceans in the warm latitudes must have decreased 20 per cent.

THE LAWS OF CLIMATIC CHANGE

All climatic fluctuations, from the very long to the very short, appear to follow essentially the same geographical pattern of change, differing only in period and in amplitude.

H. C. Willet

We shall now try to formulate the main laws of the climatic fluctuations during the Quaternary period.

All the changes all over the Earth surface correlate with changes in the heat content of the Atlantic waters received by the Arctic Basin. They were characterised by fluctuations in the winter temperature differential between the equator and the North Pole, the summer temperature differential only varying slightly.

Although the climate changed over the whole Earth at the same time the degree of temperature fluctuations varied in different zones. The greatest variations were in the polar latitudes of the Northern Hemisphere, the smallest in the equatorial zone, with moderate temperature fluctuations in the Southern Hemisphere.

All the climatic optima raised the temperature of the surface layer of the World Ocean, and evaporation increased with it. The absolute humidity of the atmosphere increased. It is only natural that during the glacial epochs the continental character of the climate and aridity became more prevalent, and during the warmer periods the continental climate receded, the moistening of the continents increased and the deserts grew less arid. The influence of the climatic optima on the marine fauna of the Arctic Ocean made itself felt most in the Atlantic sector and the least in the Pacific, because the Atlantic waters penetrated to the Pacific sector in a smaller volume and with a lower heat content. As for heat- and moisture-loving vegetation, it spread from west to east, into the depths of Eurasia, as the climatic optima

gathered strength, because the climate was always colder in the northeast of Eurasia than in the northwest. During these optima the climate became more stable and the differences between the sectors in the Northern Hemisphere were smoothed out. Even in our days, during the usual succession of the warm and cold seasons, in winter each sector of the Northern Hemisphere has its own régime of temperature and rainfall, while in summer the differences between the sectors are to some extent levelled out. And the last law is that the processes of the climatic changes during the Anthropogene are clearly reversible. This facilitates the forecasting of artificial climatic changes during a reconstruction of the natural mechanism of climatic changes.

The clear manifestation of these laws and the areas in which they operate differ—they increase with the increase in the amplitude and duration of the climatic changes.

Some laws have long since been substantiated in physicomathematical terms. Thus V. V. Shuleikin established the law of fall of the temperature anomaly during penetration of heat waves from the surface of the ocean into the depths of Eurasia, his mathematical calculations have been found to accord well with the observations of natural processes.*

This warrants a most important fundamental conclusion: the rise in the temperature of the surface waters of the World Ocean, particularly in the North Atlantic and the Arctic Ocean, is the main cause of planetary improvements in the climatic conditions.

Or, as was pointed out by L. R. Rakipova, of all the possible methods of changing the climate artificially thawing of the Arctic ice must be regarded as the most effective.

But maybe the Arctic ice cannot be destroyed? The opinions of scientists differ on this point. M. I. Budyko regards the sea ice of the Arctic as a relict of the past glacial epoch, which exists because of its high albedo and, which, once destroyed, will not recur. D. A. Drogaitsev takes the view that the albedo only has an effect in summer, and that the open surface of the basin would freeze up again in winter, when there is no radiation to be reflected

* A calculation of the present location of the pole of cold between the Pacific and Atlantic deviates from the actual location only by 6° longitude.

during the long polar night, so that the restoration of the ice sheet would be inevitable, even if we managed to destroy it completely.

It is, therefore, very important to examine the nature of floating ice, because both the method of destruction and the prevention of its regeneration depend on this. If the ice is a relict, then it would perhaps really be enough

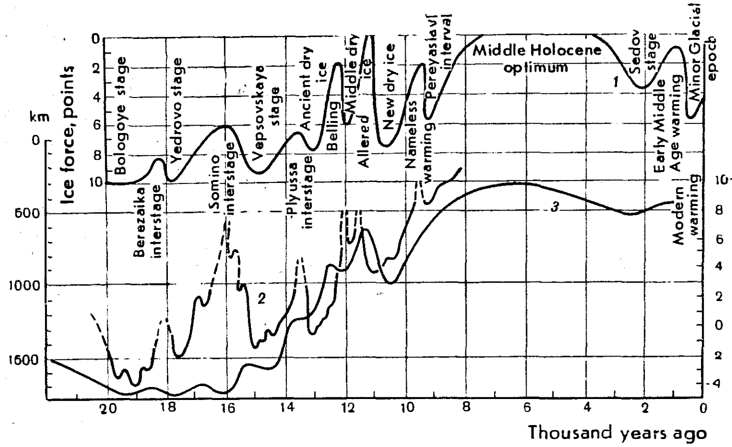


Fig. 12. Dynamics of sea ice of the Valdai Glaciation in the Russian Plain and the mean annual air temperatures in the past 20,000 years

1—dynamics of sea ice in the Northern Hemisphere;
2—dynamics of the Valdai glaciation in the Russian Plain (N. S. Chebotaryova et al., 1965);
3—variations of mean annual air temperatures in Central Europe (P. Woldstedt, 1958)

to destroy it once. If, however, it recurs periodically and inevitably as a result of the present-day processes in the Earth atmosphere and hydrosphere, we would need to take additional measures to prevent regeneration.

Our preliminary analysis of the glaciation of the Arctic Basin over a period of the last 20,000 years (Fig. 12) has shown that it exceeded the present-day glaciation amounting to 4 points over a total of 9,300 years. Twice during the Holocene, for a total of 5,000 years, the Arctic Basin was completely free of ice. And the ice sheet was unstable several times, for a total of 4,000 years, that is, it melted in summer

and froze up again in winter, but over a smaller area than in our time. In other words, during the Holocene, over a period of 9,000 years out of the 12,000, the ice conditions were incomparably more favourable than in our time.

The repeated melting and freezing of the ice sheet indicate that the Arctic sea ice is not merely a relict of a past epoch. It is rather a product of climate. That is why with the present-day advection, which is insufficient, the freezing of the surface of the Arctic Basin and the regeneration of the ice sheet would be inevitable.

Whether we are dealing with the conservative nature of the sea ice or the stability of the unfrozen surface, we must be somewhat cautious. Both the ice and the open surface are equally unstable formations. Suffice it to recall that an average of two-thirds of the sea ice on the Earth (four-fifths in the Antarctic) is renewed each year. Despite the fact that the polar latitudes of the Southern Hemisphere are incomparably more rigorous than those of the Northern Hemisphere the Antarctic ice is younger than the Arctic; the reason is that the Antarctic has a better water exchange with the warm basins (Pacific, Atlantic and Indian Oceans). Even two- and three-year-old ice can only be found in limited areas in the Antarctic, whereas a large part of the Arctic ice is three years old or more. At any rate, none of it is relict ice and it regenerates continually.

Very recently, in the 1930s, the floating ice of the Arctic Basin melted almost before our eyes. The warming gathered such speed that foreign scientists believed that if this speed continued for 50 years, vast areas would be open up to navigation during the summer seasons. But this did not happen. On the contrary, since 1940 the general and navigational position has been deteriorating.

The general circulation of the atmosphere is divided into meridional and zonal. If meridional circulation (south to north) predominates, more warm water is driven into the Arctic Basin and the amount of floating ice decreases and sometimes even disappears, as happened during the Holocene. If, however, zonal (latitudinal) circulation prevails, the advection into the Arctic Basin decreases, and the ice sheet regenerates in increasing proportions. In 1953-1957 the boundary of old ice in the sector of the Laptev Sea moved almost 1,000 km south at an average rate of

250-300 km a year. The rate of succession of phases of the surface layer (ice or water) depends on the presence of a layer of desalinated water on the surface of the basin. The lower the density of the surface water and the thicker this layer, the more stable the ice sheet. The present-day physico-geographical conditions in the Arctic Basin favour the continuous generation of the desalinated surface layer and, consequently, increase the stability of the freeze-up.

However, such generation is only possible when certain other factors are stable, which is not always the case. Thus an increased inflow of warm Atlantic water to the Arctic Basin provokes an increased run-off of cold desalinated water and ice from the Arctic into the Atlantic. With certain heat-content correlations of the oppositely flowing masses of water the cold water may carry off the incipient warming. The fluctuations discovered by V. V. Shuleikin illustrate this. Another example. The rise in temperature of the surface layer of sea water in the Atlantic and in the Arctic Basin causes an increased rainfall both on land and over the Arctic Basin and with it a desalination of the surface layer of the basin. The desalination impedes the heat exchange between the deep waters and the atmosphere, which is conducive to the development of an ice sheet. At the same time sufficiently large masses of Atlantic water may wash away the desalinated surface layer, in which case conditions favouring an ice-free Arctic will arise.

This is at variance with the thesis that the heat of solar radiation in the active layer accumulates during the summer period to an extent that ensures an ice-free Arctic Basin in winter. The thing is that the life of the ice sheet is not only controlled by the high albedo of the ice and snow, but also by other factors. The main factors which cannot be eliminated by a single destruction of the floating ice are these:

First. The continuous replenishment of the surface layer of desalinated water in the Arctic Basin: the annual inflow of 36,000 cu km of Pacific water, which has a lower salt content than the Atlantic water, and land drainage to the tune of more than 4,000 cu km annually. In 10-15 years this is capable of causing such a stable stratification of the Arctic water masses that it would considerably impede the

vertical circulation of the water and, with it, the heat exchange with the warm water underneath.

Second. The existence of a countercurrent of warm Atlantic water in the European Basin of the Arctic Ocean (Greenland, Norwegian and Barents seas) and the North Atlantic moving from south to north, and the cold Arctic water containing a mass of ice, moving south from the Arctic Basin, inhibits an increase in the Arctic Basin's heat budget. This inhibition works in two ways: first through sea advection, because increasingly cooled Atlantic water flows into the Arctic Basin, and then, as the ice sheet is engendered and subsequently develops, through a decrease in the radiation balance.

The influence of these two factors is so great that they are capable of counteracting the effect of the increased heat from the reduced albedo and of restoring the ice sheet. That is why after its destruction, while the present atmospheric and hydrospheric régime is in operation, the necessity for additional artificial sea advection remains. This is also indicated by A. S. Monin according to whom the Arctic ice, if it were destroyed, would regenerate through natural factors in the course of seven years.

So the floating ice of the Arctic is not a relict of the comparatively distant past. It is a logical consequence of the weakness of the meridional processes in the Earth's atmosphere and hydrosphere. However, this weakness is unstable.

Over the centuries and, in some exceptional cases, even over a few score years this may change its nature, causing either total glaciation or a complete melting of the Arctic Basin. That is why projects for once-and-for-all destruction of the floating Arctic ice for the purpose of improving the climate are futile. To achieve a permanent ice-free condition in the Arctic Basin it is not only necessary to destroy the ice sheet but also to do away with the forces which engender its formation. This would require a tremendous amount of heat. And this heat could be found in the World Ocean and its warm currents.

We shall now consider this possibility.

WORLD OCEAN, SEA CURRENTS AND THEIR ROLE IN FORMING THE CLIMATE

The warm currents are the hot-water heating system of the globe.

A. I. Voyeikov

The World Ocean or the Earth hydrosphere covers nearly three-quarters of the surface of the globe—361 million sq km, while the land measures only 149 million sq km.

The mean depth of the World Ocean is not very great—3.8 km. This thin hydrosphere could be likened to a membrane 1 mm thick on a globe 3 m in diameter, but it plays a vital role in the organic life and the climates of the Earth.

The ocean is the cradle of life. In the distant past the first living cells and then the Protozoa originated and developed in warm and quiet lagoons. If this liquid membrane evaporated, there would not be a single corner on the dried-up Earth for today's highly developed organic world. Moreover, the thermal régime would also be different: instead of the present-day mean January temperature of minus 30°C the mean temperature on the North Pole would be minus 80°C.

The ocean is, of all the natural surfaces of the Earth, the best absorber of solar radiation. But the same surface in another state (ice and snow) is the best reflector. Although the temperature range on the surface of the ocean and the ground layer of the atmosphere is small, the water changes its state quite often and fast within this small range. This changeability sharply affects the climate.

The ocean is a vast distiller. Evaporation from the ocean is 448,000 cu km of water a year, and from the continents only 71,000 cu km. The warmer the ocean, the more moisture evaporates. By shrouding the planet the moist air reduces the escape of heat into outer space and irrigates the land

which makes it easier for the farmer to grow abundant crops.

The ocean is a powerful planetary heat regulator. Owing to the large mass of water and its high heat capacity (3,200 times that of the air) it accumulates solar heat in summer and spends it in winter to heat the atmosphere, thereby smoothing out the seasonal changes in climate. In some instances the ocean also equalises the fluctuations between years. The continents are incapable of accumulating heat, which is why the continentality of the climate usually increases away from the ocean.

One of the most important aspects of the interaction between the Earth's atmosphere and hydrosphere is that nearly everywhere the surface of the World Ocean feeds the air masses with thermal energy, not vice versa as many scientists believed as recently as 30 or 40 years ago. It is well known today that the radiation balance of the atmosphere is negative, while that of the Earth surface is on the whole positive; the sum of both balances is, of course, zero.

The ocean water is in continuous motion and it is the general supplier of energy to the global wind systems. Hurricanes and gales energetically mix and shift the masses of water. Thus the West Winds in the Southern Hemisphere annually transport about 6 million cu km of water around the Earth, which is equal to twice the volume of the Mediterranean Sea. The surface layer (100-200 m) is particularly active. But the subsurface and even bottom layers of the ocean are in eternal motion. Sea currents carry large amounts of heat and cold. A particle of water can go around the world in the World Ocean, changing its state, heating at the equator and turning into ice in the polar waters of either hemisphere.

The sea and air currents between them equalise the temperature between the polar and tropical latitudes. Table 4 shows the temperatures of the air in accordance with latitudinal zones, both calculated and observed. The difference is the result of heat exchange determined by the circulation processes in the Earth atmosphere and hydrosphere. It is easy to see how strongly the interlatitudinal heat exchange affects the temperature of the Earth. If there were no heat exchange, the temperature in the

Table 4

The calculated mean temperature determined by solar radiation and actually observed in the Northern Hemisphere by latitudes (After Baur, cited by H. P. Pogosyan, 1959)

Temperature	Latitude, degrees									
	0	10	20	30	40	50	60	70	80	90
Calculated	39	36	32	22	8	—6	—20	—32	—41	—44
Actual	26	27	25	20	14	6	—1	—9	—18	—20
Difference	—13	—9	—7	—2	6	12	19	23	23	24

equatorial zone would have risen by 13°C and in the latitudes from 60°N to the pole it would have dropped by 22°C. The latitudes of Moscow and Leningrad would have a climate like the present-day Central Arctic, i.e., absolutely unfit for any vegetation.

Table 5 offers an idea about the quantity of heat transferred latitudinally by sea and air currents.

Table 5

Estimate of the annual heat balance of the Northern Hemisphere cal/sq cm/min (After Retien, cited by O. G. Sutton, 1961

Latitudinal zone, degree	Share of total area	Absorbed short-wave radiation	Emitted long-wave radiation	Excess or deficit (—)
90-60	0.14	0.13	0.30	—0.17
60-40	0.22	0.23	0.29	—0.06
40-20	0.30	0.34	0.32	0.02
20-0	0.34	0.39	0.29	0.10

The table shows that the income of short-wave solar radiation rapidly decreases from the equator towards the pole, which is because the Earth is round. Contrariwise, the losses through long-wave radiation remain almost invariable in all latitudinal zones because here the spherical shape makes no difference. Hence, the relative excess of heat in the latitudes below 40° and the shortage above

this boundary, which engender the temperature contrasts shown in Table 4. Actually, as we saw, the excess and shortage of heat are balanced by the interlatitudinal heat exchange effected by water and air.

The following question is of practical interest: What plays the determining role in the transportation of heat from the planetary cauldron to the planetary refrigerator, i.e., from the equatorial and tropical to the polar latitudes, sea or air?

The contributions of each differ at different times. Under the present-day conditions and in the colder past, with floating ice covering a considerable part of the Arctic Basin all the year round, the sea advection is relatively slight, but its role increases with the inflow of Atlantic water into the Arctic Basin. Different scientists give different figures for the correlation between the sea and air advections: from 1 : 2 in favour of the air exchange to 1 : 1.5 in favour of the sea transfer. But we shall not take the air advection into account in our calculations because its relative and absolute significance under ice-free conditions naturally diminishes. We shall keep the comparatively small contribution of heat in reserve as the "safety margin".

By calling the sea currents "temperature regulators" A. I. Voyeikov held that "in equalising the temperatures between the equator and the pole the air currents are very much less important than the sea currents and their direct influence in this regard cannot compare with the latter, although their indirect influence is very great" (1881).

In 1927 P. P. Lazarev built a model of oceanic and atmospheric circulation. This model showed that by running through the North Pole and bringing a large amount of heat to the polar region the oceanic currents heated it. Giving the Soviet experimenter his due, Brooks noted: "When the model reproduced the present land-and-sea distribution, the currents produced resembled existing currents even in detail.... The results are of great interest; in the models representing the warm periods ocean currents passed across the pole, whereas in the cold periods no current crossed the pole" (1952).

Brooks denied the dominant role of atmospheric circulation and held that its possible changes could not by themselves, without involving other factors, cause any major

climatic changes. He wrote: "The role of the atmospheric circulation should be regarded as regulating, sometimes, possibly, intensifying, but not engendering the major climatic fluctuations." Whereas sea currents, according to A. I. Voyeikov's apt definition, serve as heat regulators of the climate, this cannot be said of the largest circulations of the atmosphere. Of all the climate-forming factors, as B. L. Dzerdzeyevsky noted, they are, despite their dynamic character, the least constant factor.

An analysis of the bottom deposits in the Arctic Basin has also confirmed that it is precisely the sea and not the air currents that play the determining part in shaping the climate. When only little of the warm Atlantic water penetrated into the Arctic Basin the temperature in the polar latitudes dropped. The low temperature resulted not only in the restoration of the ice sheet in the basin, but also in regeneration of ice sheets on the continents.

Attaching enormous importance to the directions of the sea currents in forming the climate. A. I. Voyeikov wrote: "Can't we rightfully say after considering the main factors influencing the climate that without any change in the mass of the present-day currents and without any changes in the mean temperature of the air on the globe Greenland may again have the temperature it had during the Miocene and Brazil may again have glaciers? This requires only some changes directing the currents in a manner differing from that of today" (1881). Many years later Academician Y. K. Fyodorov suggested the necessity of thoroughly studying the possible changes in climate in connection with the deviation of a number of ocean currents. He regarded this as one of the most important areas of our research.

It will, therefore, be useful briefly to recall the characteristics of the present-day ocean currents (Fig. 13).

The most powerful warm current of the World Ocean, which exerts a decisive influence on the climate of the Northern Hemisphere is the Gulf Stream in the North Atlantic. It covers a vast area—from the Gulf of Mexico to Spitsbergen and Kola Peninsula. The part of the current referred to as the Gulf Stream proper runs from the point where the Florida Current merges with the Antilles Current (latitude 30°N) to Newfoundland. At latitude 38° its capacity amounts to 82 million cu m/sec or 2,585,000 cu km/year.

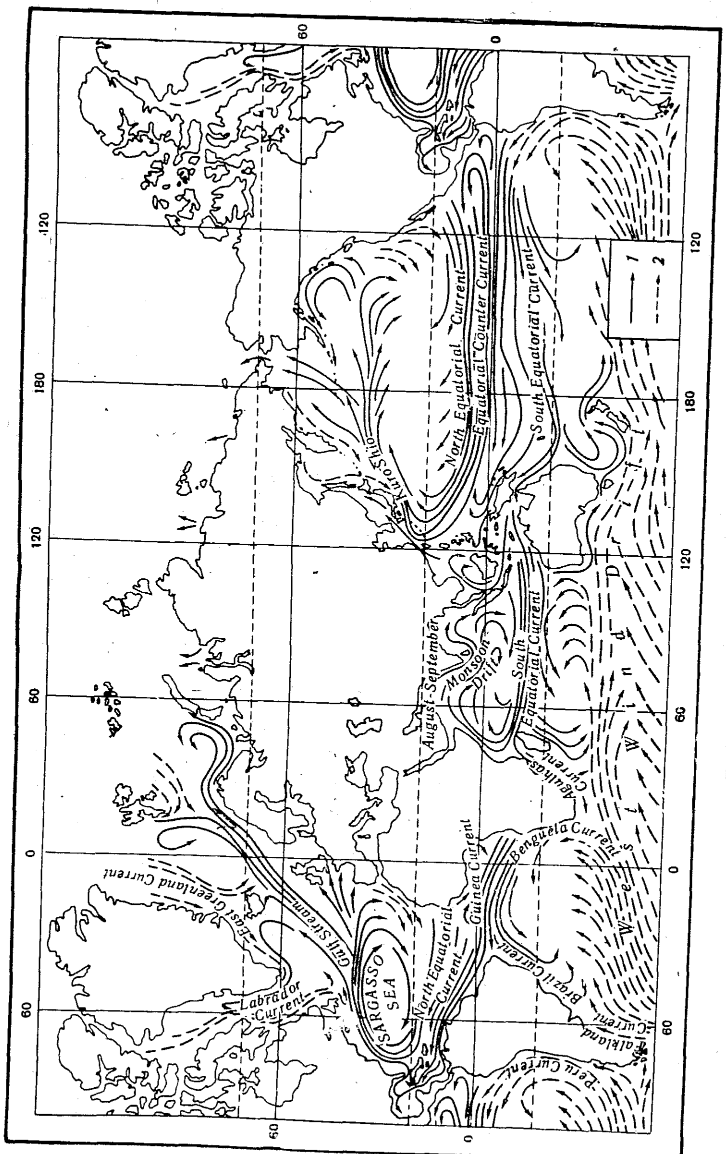


Fig. 13. World Ocean Currents
1—warm; 2—cold

In the area of Nova Scotia and the southern edge of the Grand Bank, the Gulf Stream comes in contact with the desalinated waters of the Cabot Strait and then with the waters of the cold Labrador Current. The capacity of the latter is about 4 million cu m/sec. Besides cold waters, it carries sea ice and icebergs to the area of the Grand Bank.

The ice of sea origin usually stays over the Bank, but soon after it gets into the Gulf Stream, it melts. The icebergs, however, have a longer life. After getting into the Gulf Stream they float northeastwards and even northwards again, not infrequently covering long distances all over the North Atlantic. In exceptional cases they are carried south, almost to 30°N, and east, nearly to Gibraltar.

Many icebergs spread along the edges of the Grand Bank, especially along the northern edges, where they run aground and remain until they melt to the point when their reduced weight enables them to re-float.

In addition to the sea ice and icebergs in the area of Newfoundland, the Grand Bank and Labrador Peninsula there is also bottom ice which, upon forming, comes to the surface and joins the rest of the floating ice. Since the temperatures of the Gulf Stream and the Labrador Current differ very greatly, the Gulf Stream waters cool down considerably.

After passing the Grand Bank the Gulf Stream, now called the North Atlantic Drift, flows eastwards at an average rate of 20-25 km/day and, on approaching the European shores, turns northeastwards. Beyond the Newfoundland banks it gives rise to branches which lose themselves in whirlpools. Near 25°W a large Canary Current branches off from it towards the Iberian Peninsula.

Just short of the British Isles the North Atlantic Drift sends off, on its left side, a large branch known as the Irminger Current which flows northwards, in the direction of Iceland, while the main bulk crosses the Wyville-Thomson Ridge, passes through the strait between the Shetland and Faeroe Islands and enters the Norwegian Sea.

The Wyville-Thomson Ridge and the Greenland-Iceland line form a clear boundary between the Atlantic and Arctic oceans. At a depth of 1,000 m south of the Faeroe-Shetland line, which has a depth of less than 500 m, the temperature of the water is nearly 8° higher than north of it. The salt

content at the same depth on the south side of the line is 0.3 per mill higher. The explanation of this contrast is the fact that the deep layers of warm waters in the southern part deviate to the west. To the north of the line the cold waters deviate to the east. As a result, the entire deep-water area of the Greenland and Norwegian seas is filled with very cold and dense water. These lines also separate the regions with predominating Atlantic and Arctic surface waters.

After passing through the strait between the Faeroe and Shetland islands the North Atlantic Drift flows on along the west coast of Scandinavia under the name of Norwegian Warm Current. In the area where it crosses the Arctic Circle it sends off a branch to the left, which becomes an independent warm current with a stable northerly direction all the year round.

West of North Cape, the Norwegian Current sends off the North Cape Current from its right side, which flows east to the Barents Sea. Although it breaks up into small streams east of the 35th meridian, it continues to play an appreciable role in the heat balance of the Barents Sea.

Owing to their greater density the Atlantic waters sink under the light layers of local water over a considerable part of the Barents Sea. Some of the Atlantic water penetrates into the Kara Sea. At the same time warm Atlantic water flows into the Barents Sea under a layer of local water also from the north, from the Arctic Basin along deep troughs west and east of Franz Josef Land where it comes as a branch of the deep Spitsbergen Drift.

After the North Cape Current branches off, the left branch of the Norwegian Current flows east under the name Spitsbergen Drift. On entering the strait between the Spitsbergen and Greenland its main stream loses part of its kinetic and thermal energy because the strait deflects some of the water masses and because it mixes laterally with the waters of the opposing cold East Greenland Current. The deflected water masses move first westwards and then southwards, wedge into the cold streams of the East Greenland Current and, mixing with them, form circular currents in the area of the zero meridian at 74-78°N.

The Spitsbergen Drift flows along the western shores of Spitsbergen at a speed of about 6 km a day, with a mean

temperature of 1.9°C and salt content of 35 per mill. North of Spitsbergen it goes down under the Arctic waters because of a difference in the densities and continues on its way in the Central Arctic as a deep warm current. This is not the only place, however, where the warm Spitsbergen waters flow under the cold Arctic waters. In shallow waters east of Greenland, wherever their depth exceeds 200 m, their high temperature prevails. These warm waters may penetrate deep into bays and fjords. It stands to reason that such deep penetration under the opposing desalinated waters which are fast flowing southwards and carrying deep-draught pack ice and icebergs cannot take place without a considerable loss of kinetic energy and heat. The Soviet drifting station North Pole-1 established that the Atlantic waters play a very active part in warming the upper cold layer. Even in winter, despite low air temperatures, the Atlantic waters continuously weaken the ice by acting on it from below. This applies to local ice, as well as to the ice carried out of the Central Arctic to the Greenland Sea.

It takes the waters of the Gulf Stream 11 months to reach Thomson Ridge from the Florida Strait and about 13 months to reach Spitsbergen from the Thomson Ridge.

The Irminger Current, which splits off from the North Atlantic Drift, as it approaches the northern shores of the British Isles, flows north towards Iceland. There is a fork in the current at about 63°N. The right branch flows to the Denmark Strait where it washes the western and also the northern shores of Iceland with its warm waters. In this area it comes in contact with the Iceland branch of the East Greenland Current and, mixing with its waters, cools and flows southeastwards. Beyond the fork, the left and more powerful branch of the Irminger Current turns southwest and then south and obliquely meets the stream of water and ice of the East Greenland Current. At the junction of the waters the temperature drops from 10 to 3°C at a stretch of 20 to 36 km.

Near the southern tip of Greenland the Irminger and East Greenland currents double round Cape Farewell and the entire southwestern part of the island and, under the name West Greenland Current, pass through Davis Strait into Baffin Bay.

The cold East Greenland Current, which is the main carrier for the run-off of water and the ice from the Arctic Basin, rises on the continental shelf of Asia. As it gradually withdraws from the continent to the north it forks in the area of the pole, one branch flowing to the American section of the Arctic, the other towards the Greenland Sea. Near the northeastern coast of Greenland the East Greenland Current is joined by the waters of a cold current flowing from the west along the north coast of Greenland. At 75-76°N the East Greenland Current is 175-220 km wide, while its speed increases from 2 miles a day at 80°N to 8 miles at 75°, 9 miles at 70° and 16-18 miles at 65-66°N. Its temperature is everywhere below 0°C. After passing through the Denmark Strait it comes into contact with the warm Irminger Current and together with it skirts Cape Farewell. In this area the sea ice and icebergs which get into the streams of warm water melt rapidly. During some months the zone of floating ice at Cape Farewell is 250-300 km wide, but because of the warm waters of the Irminger Current north of Cape Desolation (62°N) this ice never forms a continuous sheet and the floating ice zone does not exceed a few dozen kilometres in width.

The Labrador Current is a continuation of the cold Baffin Bay Current, which takes its source at Smith Sound. It flows along the shores of the Labrador Peninsula and then turns south along the east coast of Newfoundland; its capacity is about 130,000 cu km/year. It carries sea ice and icebergs and, as we have seen, greatly reduces the temperature of the Gulf Stream water. The waters of the Labrador Current are cold all the year round and cool the coast they wash. The Newfoundland tundra owes its existence to the cold Labrador Current. It is noteworthy that at almost the same latitude, on the other side of the Atlantic, in France, the best varieties of grapes are grown.

By examining the North Atlantic currents we become convinced that A. I. Voyeikov was right in saying that the direction of the ocean currents plays an enormously important part in forming the climate. On the very same meridian, far beyond the Arctic Circle, there is the ice-free port of Murmansk, while the ports on the Sea of Azov, 2,500 km further south, freeze up for several months in the year. Lastly, the north of the Atlantic Basin may be compared to a bathtub into which cold water is poured from two taps (the Labrador and East Greenland currents) and warm water (the Gulf Stream) through one. By regulating the taps we can change the thermal balance of the Atlantic and with it the climate of the surrounding continents. The recognition of the important role of the ocean currents in forming the climate has determined regional improvements of the climatic régime since the end of the last century by changing the direction of the warm and cold currents. At the same time extensive hydrotechnical measures have been devised to regulate and transfer the river run-off. We shall deal with the main hydrotechnical projects of meliorating the natural conditions.

IMPROVEMENT OF GLOBAL AND REGIONAL CLIMATIC CONDITIONS. EVOLUTION OF IDEAS

Discoveries almost never come extempore. They simply crown the preceding efforts of many people.

A. Y. Fersman

Man's initial attempts to modulate nature, and microclimate as one of its elements, date back to the primeval times when he dug the first irrigation ditch. Today the annual increment of the fertile lands he acquires by irrigating deserts, semi-deserts and waterless steppes amounts to hundreds of thousands of hectares all over the world. Irrigation canals stretch out for hundreds of kilometres. The largest, the Kara Kum Canal, is 1,440 km long.

A 16th-century chronicle contains an account of the first attempt in Russia to utilise the energy of a river. A citizen of Pskov tried to make the Volkhov run his flour mill. That was a bold undertaking for those days, because the river is quite big. Nowadays the joint capacity of all the hydro-electric power stations, which are being commissioned every year on rivers throughout the world adds up to many millions of kilowatts.

In Russia the names of some towns, Vyshny Volochok, Volokolamsk, Volokitino, Perevoloky and others, which stem from the root "volok" (portage)—remind one of the days when transport communications were maintained between rivers by carrying boats overland. Later, portage was replaced by hydroengineering projects. One of them, built to meet the needs of the newly founded and rapidly growing St. Petersburg, resulted in a direct water route between the Volga and the Baltic Sea. To that end a canal was dug between the Tvertsa, a tributary of the Volga, and the Tsna, which runs into Lake Ilmen. A waterway from the latter led through the Volkhov, Lake Ladoga, the Neva

and onward to the Baltic Sea. The canal was 3.3 km long, but its lock chambers were only 2.8 m wide. Nowadays continental water routes link the White Sea, the Baltic, the Sea of Azov, and the Black and Caspian seas. They are navigable to ships of 5,000-7,000 tons. The United States and Canada have built the 1,240-km Saint Lawrence Waterway along the upper Saint Lawrence River, which makes deep-draught navigation possible between the Atlantic Ocean and the Great Lakes for ships of up to 23,000 tons. Plans are afoot for transcontinental water routes across Eurasia from the Baltic and the Black seas to the Pacific Ocean, and from the Arctic Ocean way down to Lake Baikal.

The Suez and the Panama canals have been in operation a long time. New canals are projected and the old ones are enlarged to afford the passage of bigger ships.

There are also vast schemes for rechannelling the drainage of the Severnaya Dvina, the Pechora, the Ob and the Yenisei basins to the south, away from the northern inclines of the Soviet Union.

Abroad, the North-American power scheme, advanced in 1964 by a company of American consultant engineers, ranks among the major international projects of utilising water resources. The scheme envisages a partial rechannelling of water from nine major river basins in British Columbia and Alaska into a huge water reservoir in the Rocky Mountains, some 900 metres above sea level. The man-made lake will be served by dozens of pumping stations.

The bulk of the water from the reservoir will go south to California, Arizona, Texas and Oklahoma, and to northern states of Mexico. The rest will be directed eastwards across the Canadian prairies, the American states of Dakota and Minnesota, and on to Lake Superior in the Great Lakes system. The east-bound waters will irrigate the prairies of Canada and the United States and will also connect up to make an inland waterway from Vancouver on the Pacific, through the Great Lakes and the Saint Lawrence Waterway right to the Atlantic coast.

Once the mammoth project is completed, it will improve the water supply in seven Canadian provinces, thirty-three states in the USA and three of the most arid states of Mexico. The volume of water to be transferred annually

is estimated at 214 cu km. The project, calculated to cost $ 100,000 million can be built in stages and should be finally completed within 30 years. The authors expect it to provide the United States with enough water in the next 100 years.

The scheme has been officially approved by the US Committee on Public Works.

Other projects concern the irrigation of the Sahara with sea and river waters. The earliest was devised in the last century by the French engineer Roudaire. His idea was to flood Melgir and El Garsa, the lowland regions, with water from the Mediterranean. At the turn of the century a project was advanced in France to create the Sahara Sea equal to half the size of the Mediterranean. It was that the new sea would moisten the climate in North argued Africa.

A team of Italian and German engineers recommended irrigation of the Sahara with water from the Congo by damming the river and setting up a huge reservoir, the 800,000-sq km Congo Sea. The Ubangi and the Shari would carry the water from there to Lake Chad. After filling the lake, the surplus water would flood 1,300,000 sq km of land and run down towards the Mediterranean, giving birth to another Nile. However, the feasibility of this project is doubtful since the area flooded would be upwards of 2,000,000 sq km, which would cause excessive evaporation. Also rich oil and gas deposits have now been found in this zone.

In 1928 the German engineer R. Sergel proposed to change the climate in South Europe and North Africa by lowering the level of the Mediterranean. He proposed building dams in the Gibraltar and the Dardanelles straits. The Gibraltar dam would isolate the Mediterranean from the influx of Atlantic waters, and so evaporation would reduce the level of the Mediterranean at a rate of 1.5 m a year. A 200-m drop below the present level would uncover 600,000 sq km of land. Further water losses as a result of evaporation could be replaced by regular injections from the Atlantic Ocean and the Black Sea. And the passage of water through the dams could provide 120 million kilowatts of electric power. In Western Europe some people still support Sergel's project in spite of all of its many serious shortcomings.

India, Australia, Egypt and some other countries which suffer from drought are working out major irrigation projects and putting them into practice.

But more and more thought is being given to the idea of using sea currents for the thermal melioration of climate. Local, major regional and, lately, even global projects are being put forward. They concern different areas in the World Ocean.

ATLANTIC SECTOR

As we know, two big ocean currents—the warm Gulf Stream, from south to north, and the cold Labrador Current, from north to south—wash the eastern shores of the United States. The Earth's rotation deviates the cold current to the west, raising a cold barrier between the northeastern coast of the United States and the Gulf Stream. The difference in the temperatures between the cold barrier and the Gulf Stream is up to 20°. The breath of the cold waters affects the shoreline for 1,500 km south of the Gulf of Saint Lawrence. To counteract the ill effect, the following projects have been put forward.

The idea of bridging the Strait of Belle Isle with a blank dam dates back to the late 1870s. This would keep the cold waters away from the Gulf of Saint Lawrence. The author calculated that the project would minimise the cold effect for a considerable distance along the North American eastern coastline.

In the 1890s it was suggested that the Florida Strait be dammed, thus opening the way for warm waters from the Gulf of Mexico through a canal cut across the root of the Florida Peninsula. The engineers argued that the gulf waters would neutralise the cold from the countercurrent. The project was approved by the US government, but later it was severely criticised by the well-known climatologist Koppen.

Another suggestion was to draw the confluence of the Gulf Stream and the Labrador Current to a point 400 km further off to the east, to reduce the cold effect of the Labrador Current on the American shores. The project envisaged a 400-km dam running eastwards across the shallows of the Grand Bank. The authors believed that the scheme would augment the heat content of the Arctic-bound Gulf Stream

waters, which would, in the long run, cause the Arctic Ocean's ice sheet to contract and eventually to disappear.

In 1955 F. Smoll produced a plan for ridding the Gulf of Saint Lawrence of ice by bringing the deep and warm Atlantic waters up to the surface. The idea was to make use of air bubbling or inclined planes which would put to work the kinetic energy of the warm currents. The author hopes that his plan will find application in a number of places in the northern latitudes right up to the Arctic Basin.

A few years ago C. Rougeron recommended damming certain straits of the Arctic Archipelago to prevent Arctic waters and ice from entering Baffin Bay. The author maintains that the arrested flow would go down the Bering Strait into the Pacific Ocean; the mean January temperature in Hudson Bay would rise from —25° to 0°C; the Great Lakes and the Gulf of Saint Lawrence would be ice-free; and a milder climate would settle down over vast areas in Canada and the northern United States.

In 1959 Rougeron came out with the idea of blocking the Davis Strait (350 km) with a dam of the tidal power-plant type which would admit flood waters from the Atlantic and let them pass to the straits of the Arctic Islands. Once the Canadian waters are completely free of ice, the rigorous climate in North Canada would be softened down to something like the West European climate.

THE PACIFIC OCEAN SECTOR

The Bering Strait Dam Project is one of the first schemes designed to improve the climate in the Far East and the adjacent regions. It was originally advanced at the end of the last century, and since then engineers have taken it up and modified it repeatedly.

The original plan was to stop the flow of cold water and ice from the Arctic Basin, because at the time it was generally believed that this flow cooled the Kamchatka Current, and the Kamchatka Current carried the Arctic cold to the Kurile Current (Oya Shio). It was also assumed that it was these currents that had the greatest impact on the Soviet Pacific coast, the Japanese Islands and on most

of Asia's east coast. Subsequent studies proved that the flow of Arctic waters had only a minor effect on the climate of the eastern coastline, and that the Arctic Basin itself was replenished by comparatively warm waters from the Pacific. So the project was completely revised, and the Bering Strait Dam was assigned the opposite task of stopping the outflow of warm Pacific waters into the Chukotka Sea, thereby improving the heat conditions of the Bering Sea and the surrounding expanses. It turned out, however, that the impact of the Pacific waters, which are comparatively warm in summer, was exaggerated, too. This is only felt in the southern part of the Chukotka Sea.

In 1898 Fridtjof Nansen voiced the opinion that if the Bering Strait were wider and deeper, the far-off extension of the warm Kuro Shio, which passes through it, would have been larger and more powerful and would have yielded so much heat that the contrast in the climates in the north and the south would be less noticeable than it is.

The opinion of such a great authority on the Arctic rekindled the interest in the project. The ideas revolved around one focal point: artificial generation of additional heat in the Pacific waters which enter the Arctic Basin.

Professor D. White of the University of California suggested setting up atomic plants for the purpose. The Soviet engineer A. I. Shumilin put forward a complex plan, envisaging mechanical transfer of the incoming Pacific waters into the Bering Strait, softening in this way the climate in the east of Soviet Asia and the northwest of North America, and the building of a railway along the dam to link Chukotka and Alaska.

Other projects pursued local aims, but they were all governed by one common desire: to bring the warm waters of the Kuro Shio nearer and to improve the thermal régime in the northeast of the Asian mainland.

In 1891 I. Kasatkin suggested that a blank dam should be built in the Tatar Strait so as to prevent the cold current from the Sea of Okhotsk from cooling the coastline between the Amur estuary and Vladivostok. The author declared that the climate between the Tatar Strait and the Sikhote Alin mountain range would be improved and that Vladivostok harbour would become completely ice-free. But

when it was presently established that there was no such cold current, the project was dropped.

Then people came up with ideas of drawing the warm waters of the Sea of Japan into the Sea of Okhotsk with the help of a dam in the Tatar Strait. Some projects (N. G. Romanov's, for one) envisaged water seals to transfer the warm waters brought by tidal bores. At high tides or northward bores the seals would open the way to warm waters from the Sea of Japan into the Sea of Okhotsk, and close it in reflux periods. But calculations proved that the effect would not be large enough.

The Soviet engineer N. M. Budtalayev suggested reinforcing the south-to-north flow with pumping units on the dam. N. A. Belinsky and A. V. Trufanov (both USSR) had their own method for drawing warm waters into the Sea of Okhotsk. They said that it could be done by building a 100-km canal across the base of the Kamchatka Peninsula, from the Penzhina Bay to the Bering Sea. The authors calculated that the continual flow of water from the Sea of Okhotsk into the Bering Sea would force warm Pacific waters, including waters from the Kuro Shio, into the Sea of Okhotsk through the straits in the Kurile Archipelago. They believe that the project would sharply improve the climate in the Far East.

In 1962, P. I. Koloskov developed his earlier idea of diverting the lower drain of the Amur towards Lake Kizi and to the Taba Bay so as to warm up the adjacent territory. onward

All these schemes were concerned with some climatic improvement in the east, none of them directly involving the Arctic Basin.

But there are projects which aim at raising the temperature in the Arctic Ocean itself.

In 1930 the Soviet sea captain, E. S. Gernet, came to the conclusion that the elimination of Greenland's ice cap would result in the obliteration of ice in the Arctic. D. Fletcher, commander of an American drifting station, is of the opinion that the climate in the Arctic Basin and the neighbouring regions can be improved by the artificial dispersal of clouds in summer. H. Wexler of the US Weather Bureau contends that it is necessary to reduce the Arctic

Ocean's infrared radiation by exploding "clean" hydrogen bombs, which would also artificially increase the atmospheric humidity.

M. I. Budyko put forward the following plan of destroying the Arctic ice sheet: to cover the ice surface with a thin layer of dark powder for a span of one or two years, to intensify the absorption of solar radiation and stimulate the ice sheet to melt; to cover the surface of the North Atlantic or the ice-free Arctic seas with a monomolecular film which would substantially change the thermal régime of air and water in the Arctic by diminishing the radiation heat by evaporation.

In one of his subsequent works M. I. Budyko advocates a simultaneous application of the monomolecular film and cloud dispersion, as well as the cultivation of special seaweed which grows on ice and just like the dark powder decreases the albedo and stimulates melting.

In 1963 Professor V. N. Stepanov of the Institute of Oceanology, USSR Academy of Sciences, suggested that the Wyville-Thomson Ridge between the Shetland and the Faeroe islands should be shortened by underwater explosions to increase the cross-section of the straits. This, the author believes, would increase the influx of warm Atlantic waters into the Arctic Basin to a point when the drift ice diminishes.

There have also been suggestions about putting the warm waters of the North Cape Current to work (V. N. Avdeyev, V. P. Pyankov and others), but no satisfactory solution has yet been found. The authors examine only some aspects of the problem, without finding an overall solution which includes safety, technological and constructional feasibility, expenses, reliable climatic forecasts, and so on.

But what kind of safety can there be when it comes to hydrogen bombs, however clean the bombs, if they are used in large numbers—and the Arctic Basin's geographical and hydrological lay-out is such that a great many H-bombs would be needed.

The technical feasibility of any scheme is essential and so is practicability. It would be almost impossible to keep a monomolecular film intact on the open sea. The film would break too easily, and the winds would blow it away in a comparatively short time as has been proved by exper-

iments in both artificial and natural environments. Here a recent accident at sea seems to have some bearing: on March 18, 1967, the tanker *Torry Canyon*, with 100,000 tons of oil aboard, broke in half off the Cornwall Peninsula (Great Britain) and sank. The sea was covered by a thin layer of oil which had a strong resemblance to a monomolecular film. But the oil patch was broken up by waves and dispersed by winds in quite a short time. Some of the oil was carried off to the southwest into the open sea, and the rest, to the shores of France. Two weeks later the economy of Brittany suffered a great blow from the mass extinction of sea birds, fish and oysters.

It may be possible in theory to spread a monomolecular film over vast sea, but in practice we would run into insurmountable technical obstacles.

When advancing one or another project we must ascertain beforehand its technical feasibility and the potentialities of modern industry and power engineering. The deepening of the Wyville-Thomson Ridge, as envisaged in one project, in the most favourable place—between the Faeroe and Shetland islands—would entail the removal of 3,000-5,000 cu km of compact soil to a distance of at least 25 or 30 km. Since the bottom there lies half a kilometre below sea level this would be a hopeless task at present even if we used atomic demolition charges. Besides, the project has another grave defect: there would be no control on the influx of warm waters.

Economic problems should also be taken into account, though in relation to the other problems one might not expect any difficulties here since climatic amelioration is expected to result in tremendous advantages. Nevertheless, we cannot wholly discount the question of capital investments and subsequent operating costs, construction time and reimbursement prospects.

But, although weighty, these are still only preliminary considerations. The main problem is the extent to which the future climatic changes would follow the present pattern and how reliable and reasonable would the warming be. In other words, prognosis is of paramount importance. Of all the methods of forecasting, the most reliable is the one that is based on the studies of past climatic changes on our planet over millions of years.

In previous chapters we said that paleogeographic and geological studies had revealed that in the Quaternary Period climatic and ecological changes with clear signs of reversibility occurred quite frequently. However, in spite of all their duration and fluctuations, the changes directly depend on the advection of oceanic heat into the Arctic Basin. That is why we should place trust only in projects which recognise that Atlantic waters bring heat into the Arctic Basin and which link climatic forecasts with the rise in heat content.

As long as there are no reliable guarantees of climatic amelioration, no state will consent to global modifications. Besides, while improving the climate in a particular place, we must take care that it does not deteriorate somewhere else. We must also safeguard the normal evolution of fauna and flora and avoid morbid symptoms. The process should be reliably controlled so as to rule out the possibility of harmful effects on nature's intricate mechanism and the interaction of its component parts.

The countries which are interested in climatic amelioration have enough technical and power potential to tackle the job at any time on a global scale.

The general plan of climatic amelioration should envisage the following.

We should create a direct flow of warm Atlantic waters to the Pacific Ocean through the Arctic Basin so as to protect them from the fatal impact of the cold polar waters. The northern offshoots of the Gulf Stream would be given free access to the North Pole and onward to the Pacific Ocean via the Chukotka and the Bering seas. From there, being more saline and, consequently, denser, the Gulf Stream waters will flow southwards as deep-sea currents. Eventually, when the Arctic becomes warmer, their temperature will be higher than in the Pacific's northern regions, and so they will rise to the surface. On their southward course they will join the warm waters of the Kuro Shio.

IS THE POLAR GULF STREAM POSSIBLE?

> The sea surface has a special role. Its temperature can probably be changed with the help of big hydroengineering structures for re-directing sea currents. That would, apparently, be the most realistic interference in global climate-forming processes.
>
> *Y. K. Fedorov*

To ascertain the possibility of giving birth to a Polar Gulf Stream, we must first study the essential oceanographic data relevant to individual areas in the northern part of the World Ocean: water and thermal balances, the properties of water masses, their stratification and dynamics, ice cover, and so on.

Let us begin with the Arctic Ocean and its basin. We may be helped here by data furnished by the USSR Arctic and Antarctic Research Institute which has been investigating that part of the World Ocean for many years. According to the Institute, every year the Arctic Ocean is replenished by 338,000 cu km of waters of different origin (298,000 cu km from the Atlantic by way of the Faeroe-Shetland Strait; 36,000 cu km from the Pacific via the Bering Strait, and 4,000 cu km from river drainage). We are discounting rain and snow precipitation on the assumption that they are balanced by evaporation. Since the sea level remains static, it is clear that the basin dispatches the same quantity of water. And indeed, the water leaves the ocean by several channels: the Shetland Strait—163,000 cu km; the Denmark Strait—135,000 cu km; the Arctic Islands straits—40,000 cu km.

But this exchange is not without effects. One of the Arctic Ocean's principal acquisitions in the process is higher temperature. The Atlantic waters lose $1{,}922 \times 10^{15}$ Cal to the Arctic Ocean per annum against 26×10^{15} Cal supplied by the Pacific, i.e. the Atlantic supplies 98.7 per cent of the heat, the Pacific only 1.3 per cent. In other words, the Atlantic contributes 73 times more heat to the Arctic Ocean than the Pacific.

The heat injected is distributed as follows: $1{,}410 \times 10^{15}$ Cal (71 per cent) within the limits of the Norwegian and the Greenland seas; 291×10^{15} Cal (16 per cent) in the Barents Sea and 247×10^{15} Cal (13 per cent) in the Arctic Basin.

But actually the sea currents surrender much less heat to the Arctic Ocean. Part of the heat is carried back to the Atlantic by the warm Atlantic currents which flow under the cold and desalinated East Greenland Current through the Denmark Strait. But the main outflow of heat is in the waters which flow from north to south through the western half of the Faeroe-Shetland Strait. They comprise the 163,000 cu km which rob the Arctic of more than half the bounteous gift sent by the warm Atlantic through the Faeroe-Shetland Strait. At a mean temperature of 4° the Atlantic gets back roughly 700×10^{15} Cal of unused heat annually. These backflows take away again one-third of the heat the Arctic Ocean receives.

We must also note that although the Arctic Basin is twice the size of the European Basin, it absorbs a mere 13 per cent of the Atlantic heat, while the remaining 87 per cent is consumed by the European basin. This is due to the counterflow of warm and cold currents. But if the Atlantic waters could avoid meeting the cold waters, i.e., if they were to flow directly to the pole and on into the pre-Pacific sector, the heat loss would be drastically cut.

We could prevent the cold counterflow from cooling the Atlantic waters by turning the Atlantic waters into the Pacific and keeping them from returning, cooled, into the Atlantic, as they do under the present water exchange. The volume of this exchange can be ascertained from the Arctic Basin's water balance (in thousands of cu km/year):

Debit		Credit	
Drainage into the European Basin	135	Atlantic waters	135
Drainage into Baffin Bay	40	Pacific waters	36
Drainage into the Bering Sea	0	Land drainage	4
Evaporation=precipitation	—	Precipitation=evaporation	—
Total	175	Total	175

If we built a dam across the Bering Strait, it would keep out the Pacific waters. Then, to prevent the cooling of the Atlantic waters by the Arctic, we should have to pump 139,000 cu km/year of water from the Chukotka Sea into the Pacific.

When they enter the Arctic Basin, the Atlantic waters have a low temperature—just 1.9°, but the temperature of the Pacific waters is still lower—about 0.8°C. Hence, the heat content of the Atlantic waters is 256×10^{15} Cal, while that of the Pacific is only 26×10^{15} Cal, i.e., a tenth as much.

The balance shows that the inflow of the Atlantic waters is almost four times as great as the inflow of Pacific waters. So it would be reasonable to assume that the Arctic waters are in actual fact waters taken over from the Atlantic and that the Arctic Basin itself is, in essence, an outlying cold gulf of the warm Atlantic.

So far we have been looking at what takes place on the surface of the Arctic Ocean and its boundaries with the Atlantic and the Pacific. We have traced whence and where the currents flow, and we have specified their size and heat content. That is all important but this data is insufficient for the purpose of creating a Polar Gulf Stream. The waters which fill the Arctic Basin, and this is true of all the other basins in the World Ocean, are by no means homogeneous. They all have their own properties and oceanographic peculiarities. That is why we must know for certain the main parameteres (temperature, salt content and density) of each water mass in each of the basin's vital regions in both horizontal and vertical planes; we must find how and where the water masses lie in relation to each other, i.e., we must trace their stratification. To visualise all these complicated interactions in the water layer we shall have to investigate all its levels right to the bottom.

The Arctic Ocean covers an area of 13.1 million sq km, of which 8.75 million sq km are in the Arctic Basin. In winter up to 11 million sq km are covered by ice (this includes the whole of the Arctic Basin). In summer the ice sheet contracts to 8-9 million sq km mostly because of the thaw in the European Basin and Baffin Bay; in the Arctic Basin itself the ice melts sparsely and only in the offshore areas of the outlying seas.

The average thickness of the ice is around 2.75 m and the total mass is up to 25,000 cu km. In summer, 20 per cent (5,000 cu km) of this volume melts, and about 3,000 to 4,000 cu km of ice are driven to the Greenland Sea and to Baffin Bay.

Fig. 14 shows the normal distribution of ice on the surface of the Arctic Basin at the end of winter.

Table 6 gives an idea about the stratification of water masses in the basin.

The Arctic surface waters make up the first layer of water covering the vast expanses from Spitsbergen to the Chu-

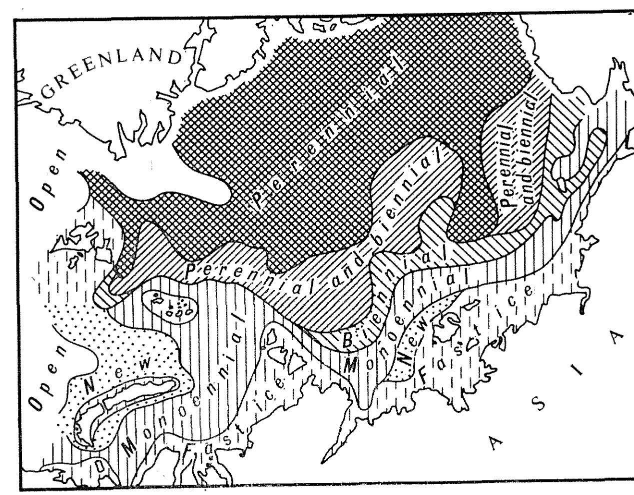


Fig. 14. The state of the ice in Central Arctic in April-May 1956 (A. F. Laktionov and V. A. Shamotyev, 1957)

kotka Sea. Their origin is complicated. They are a mixture of waters from the outlying seas desalinated by river drainage, Pacific waters, waters formed by the melting of snow and drift ice, and atmospheric precipitation which settle on the surface as rain, snow and hoarfrost. The average thickness of the surface water layer varies. In the pre-Pacific sector it goes down 82 metres; in the pre-Atlantic sector it is less than 30 metres. The mean vertical temperature is close to −1.7°, but the salt content is very low—30.00

Table 6

Character of water masses in the central section of the Arctic Basin (V. T. Timofeyev)

Water layers	Thickness in m	Volume in 1,000 cu km	Tempe-rature °C	Salt content ‰	Density σ t
Arctic surface	64	321	—1.75	30.00	1.0245
Intermediate upper	172	864	—1.75	34.60	1.0278
Atlantic	630	2,738	+1.50	34.90	1.0279
Intermediate lower	1,932	4,540	—0.40	34.93	1.0280
Bottom	2,202	2,454	—0.80	34.96	1.0281

per mill, which fact deprives it of so much density that its supremacy on the basin's entire surface is practically unchallenged.

The surface waters move together with the ice cover from the more frigid east to the warmer west. The flow provides 70 per cent of the energy that drives them towards the Greenland Sea and Baffin Bay, the remaining 30 per cent is provided by the winds. The water moves faster in the basin's uppermost layer, but its motion slows down with the depth, and at 100-200 metres below sea level the water comes to a standstill.

However, this takes us down to the intermediate upper water layer which occupies the next plane. The temperature there rises from —1.7° to 0°, salt content comes up to 34.60 per mill. The layer is composed of a mixture of surface waters and the underlying warm Atlantic waters. In the pre-Pacific sector the layer is nearly 190 m thick, and in the pre-Atlantic, almost 150 metres.

The layer of warm Atlantic water is deeper down. Naturally, the layer's temperature is much higher. We have already said that the Atlantic waters enter the Arctic Basin at an average temperature of 1.9°. At its centre it is a little higher, 2-3°, but as the waters advance eastwards, the temperature gradually drops to the ultimate 0.5-0.6° at approximately the same depth in the pre-Pacific sector (Fig. 15). In the upper and lower margins the temperature drops to 0°. In comparison with the overhead water masses,

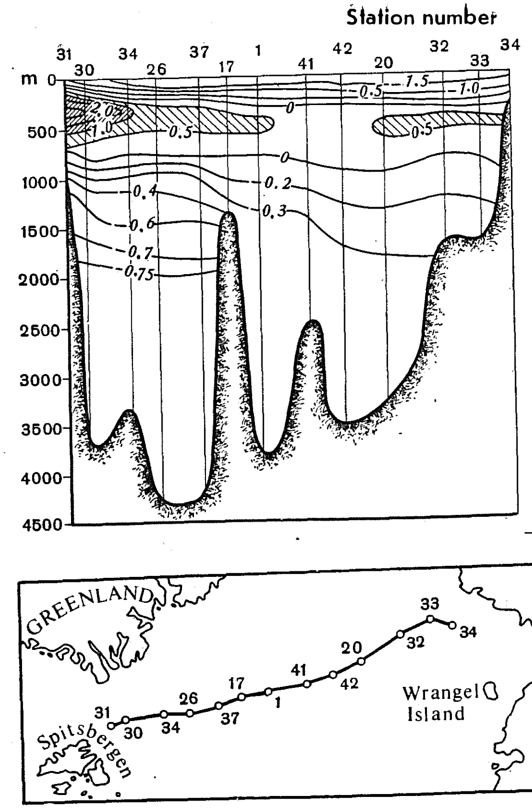


Fig. 15. The distribution of water temperatures (°C) in a cross-section of Spitsbergen-Chukotka Sea (V. T. Timofeyev, 1960)

the layer's salt content rises slightly—to 34.9 per mill, i.e., by a mere 0.3 per mill.

The Atlantic waters are carried into the Arctic Basin by the Spitsbergen Current. After they pass through the strait between Spitsbergen and Greenland, they spread out fanwise and immediately sink to the lower levels. Their submersion beneath the cold waters is of paramount importance in the formation of the global climate.

The deeper down, the denser the water becomes. Sea water masses occupy definite vertical positions according

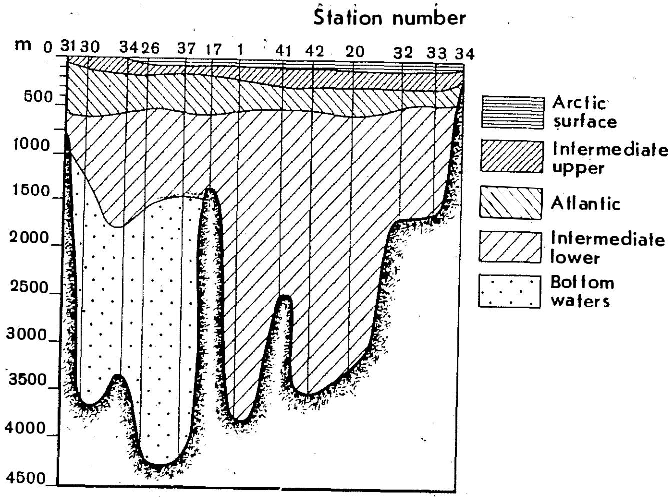


Fig. 16. The distribution of water masses in a cross-section of Spitsbergen-Chukotka Sea. For the position of the cross-section, see Fig. 15

to density. This rule is strictly adhered to. Density depends on salt content and temperature: the higher the salt content and the lower the temperature, the heavier the water becomes; its extra weight begins to pull it down to the lower levels. And conversely, lower salt content and higher temperature, and, consequently, lower weight will keep water nearer to the surface. Though the Arctic surface waters are colder than the Atlantic (their temperature is —1.75°), they are still lighter because they contain very little salt—only 30.00 per mill. This comparatively low salt content has helped them to float up to the very surface. The Atlantic waters are, so to speak, drowned by their high salt content (34.9 per mill).

Fig. 16 illustrates the arrangement of the layers of water. The cold Arctic surface waters protect the ice cover from the warmth of the Atlantic waters, and prevent it from melting. Were it not for the cold surface layer, the warm waters would rise, reach the ice sheet and melt it away; the warm Spitsbergen Current would continue on its way to the pole and beyond, not in the lower levels, as at present

but on the surface, and so the current would exercise a greater influence and help to create the Polar Gulf Stream.

The upper margin of the Atlantic waters with a temperature of 0° sinks to a depth of 180 metres in the pre-Atlantic sector and to 200-300 metres in the pre-Pacific sector. On the continental incline the depth decreases to 150 metres, because it is shallower there, being nearer to the shore. In the pre-Atlantic sector, the layer of Atlantic waters varies from 650 to 750 metres in thickness, but further east the layer gets diffused into the upper and lower intermediate waters and loses heat. Only a comparatively thin layer of water, 150-200 m thick, reaches the Chukotka Sea without losing its positive temperature. In this way more than two-thirds of the layer disappear.

What happens to those deep-flowing warm Atlantic waters? The deflecting Coriolis force presses the bulk of those waters against Eurasia's continental incline, and they move on towards the Chukotka Sea (Fig. 17). Another portion, failing to pass the incline on time, spreads to the left in the direction of its movement and, after completing a half-circle, returns to the Greenland Sea. A similar left turn from the Eurasian mainland is made by the remainder of the warm waters which succeed in reaching the Chukotka Sea.

It takes the Atlantic waters one and a half years to cover the distance from Spitsbergen to the Kara Sea, two and a half years to the Laptev Sea, four years to the East Siberian Sea, five years to the Chukotka Sea, and six years to the Beaufort Sea. All in all, the Atlantic waters take eight years to go round the Eurasian and American continental inclines and return to the European Basin.

It would be interesting to recall here an episode from the three-year drift of the *Sedov* in the Arctic Basin. The sailors saved fuel by lowering the frozen water hoses into the sea to a depth of over 200 metres where the temperature is 2°C. The next day they hauled the hoses aboard and found them completely melted. That was how the polar explorers made use of the heat brought into the centre of the Arctic by warm currents.

Another story is of a completely different nature. It is generally known that the temperature of the bottom layer of water is only 1.5-2.0° above zero even at the equator.

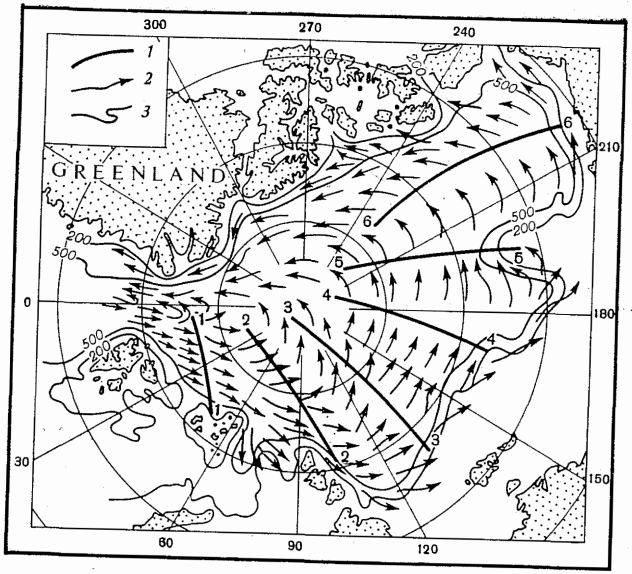


Fig. 17. The movement of Atlantic waters in the central part of the Arctic Basin (V. T. Timofeyev, 1960)
1—time isolines; 2—direction; 3—isobaths 200 and 500 metres

A century ago, when there were no refrigerators yet, the officers of the corvette *Challenger*, on the first major oceanographic expedition, used the bottom water and silt to cool their champagne. As has been pointed out, the cold waters can only get to the equatorial region from the polar regions where they submerge to the maximum depth and gradually flow towards the equator.

Beneath the warm Atlantic waters lies the layer known as the lower intermediate water. The temperature there drops from 0 to minus 0.4°, and the salt content rises to 34.93 per mill. In the pre-Atlantic sector the lower intermediate water is found from a depth of 800 m, with its lower margin at 1,500-2,000 m below sea level. In the pre-Pacific sector the layer begins higher up: at 700 metres, and continues right to the bottom, so here the lower intermediate waters and the bottom waters are one and the same.

The last layer is the bottom waters. In the pre-Atlantic sector their temperature ranges from minus 0.8° to minus 0.85°C, but the salt content is constant throughout the layer, 34.96 per mill.

So we know now the stratification of the warm Atlantic waters between the upper and lower levels in the Arctic Basin.

But what happens to the Pacific waters in the Arctic Basin?

We pointed out that the Pacific waters enter the basin in comparatively small quantities—36,000 cu km/year. If this water were evenly distributed over the whole surface of the Arctic Basin, the layer would only be 4 metres. On entering the Chukotka Sea the mean annual temperature of the Pacific waters is slightly below 1°, and the salt content is 32 per mill (Fig. 18). The comparatively low salt content accounts for the water's low weight. This is why, instead of staying down, like the Atlantic waters do, these waters stay nearer the surface, and become part of the surface layer with low salt content. Once out of the Chukotka Sea, the Pacific water, being less dense, flows at a depth of only 50-100 metres. Spreading over the whole of the Arctic Basin, it helps the Arctic surface waters to set up the shield which protects the ice cover from the heat of the Atlantic waters underneath. So, in the final count, the Pacific water helps the cold, and not the heat.

What then is the interaction between all these water masses, each distinguished by its own peculiar features, its own position and course in the general circulation of water?

It must be stressed that the water masses are moderately stable. Their circulation in the heart of the Arctic Basin is certainly not chaotic, they slide gently between surfaces of equal density. The varying density prevents vertical movement. Distinct layers, each with its own particular level, separate them from one another according to density. Naturally, the layers intermingle with one another, but only partially.

Fig. 16 illustrates the distribution and movement of the water masses. For example, as soon as the layer of Arctic surface waters, moving from east to west, passes the polar region, it begins to dwindle, forms a kind of wedge, and beyond latitude 85°N it disappears altogether.

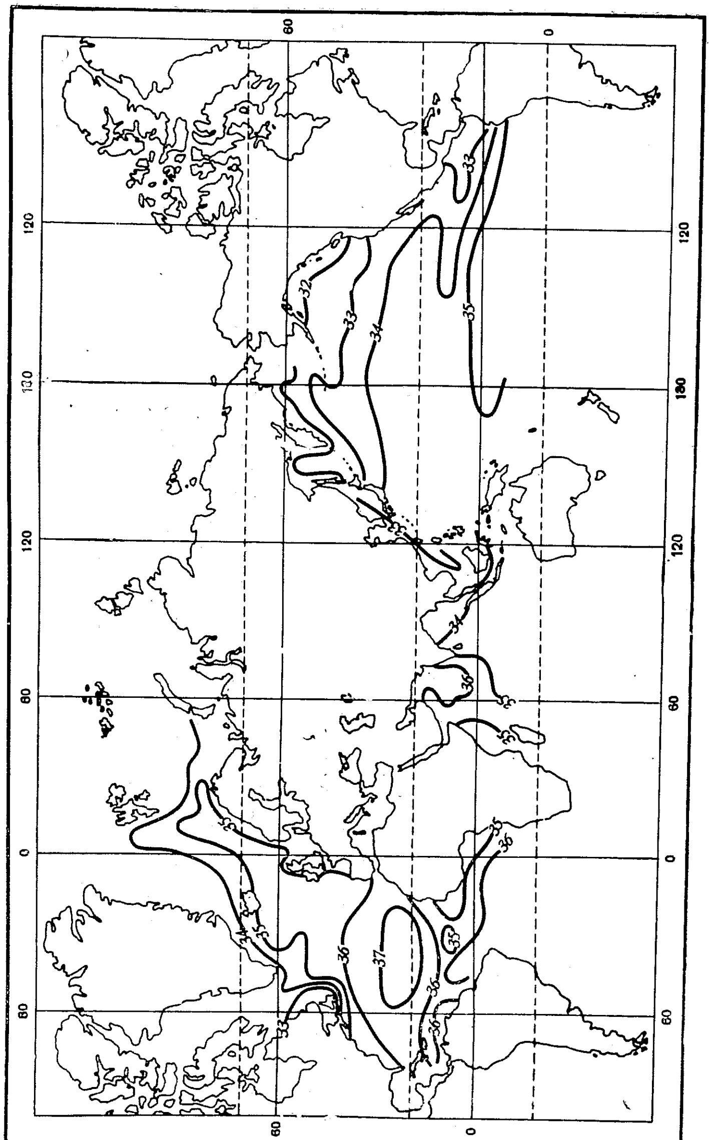


Fig. 18. Salt content of Atlantic and Pacific surface waters in August ($^0/_{00}$). (V S. Nazarov and A. M. Muromtsev, 1954)

This happens because the layer gradually mixes with the upper intermediate water under it as it moves westwards. The layer of warm Atlantic water also shrinks, as it moves from west to east, because it mingles with the upper and lower intermediate waters, and surrenders its heat.

It should be stressed, however, that the parameters of the water masses, their salt and heat content, consequently, their density, are not stable. They change in the course of years and ages. When the influx of Atlantic waters is heavy but brief, the temperature rises only slightly since it is retarded by the immediate and swelling backflow from the Arctic Basin into the Atlantic. The backflow mainly drives Arctic ice and water. Growing in size, it absorbs the additional heat from the reinforced Atlantic waters.

But when the influx of the warm Atlantic waters takes a long time to grow, the heat content increases gradually at the expense of the two upper layers, the Arctic surface and the upper intermediate. Their thickness begins to decrease, and they no longer protect the ice sheet. So the ice becomes thinner and, in summer, melts completely here and there. The impact of the warm Atlantic waters on the Arctic Basin grows stronger, and a general warming sets in, as happened just recently. When the influx of warm Atlantic waters is very strong, the ice cover becomes a seasonal phenomenon, as happened in the early Middle Ages; it melted in summer and froze in winter. Finally, the influx can be so great that the temperature of the surface layer is above zero even in winter. That happened in the Neolithic period, some 4,000 to 6,000 years ago.

We have pointed out that if we wanted to heat the polar latitudes, we should, instead of simply destroying sea ice, eliminate the two basic causes generating it: the Arctic desalinated surface layer which prevents the heat rising from the Atlantic waters below, and the cold impact of the East Greenland and the Labrador currents on the warm currents of the Gulf Stream system.

How can that be achieved?

The desalinated layer owes its origin to three sources: the shore drainage, which brings 4,000 cu km of water; the Pacific Ocean which provides 36,000 cu km, and melting ice which, in summer, produces 3,000-5,000 cu km of fresh

water. If the ice cover were eliminated, its contribution would, of course, fall out. A dam at its entrance could isolate the Arctic Basin from the Pacific waters and could also be used to transfer water from the Chukotka Sea to the Bering Sea. Since the lightest waters, i.e., the waters with the lowest salt content will be the first to be pumped off, the effect of the shore drainage, which will continue to be the main source of desalination, would be considerably reduced.

Then we would have to overcome the cooling effect of the Arctic waters on the warm waters of the Gulf Stream system. That effect is a far-reaching one, and before looking into it, we shall once again have to study the chart of the North Atlantic sea currents (Fig. 19).

At New York's latitude (39°N) the cold waters of the Cabot and the Labrador currents wedge in between the Gulf Stream and the east coast of the United States. They increase in volume towards the north, and their temperature, naturally, drops. Though the cold and warm waters move in the opposite directions, parallel to each other, the warm waters rapidly give up their heat, because both currents flow on the surface.

Near Newfoundland, the Gulf Stream and the main stream of the Labrador Current meet at an oblique, almost right, angle, and intertwine, producing a motley of temperatures. If we were to draw a chart of temperatures at the junction, it would resemble a kaleidoscope. There have been cases when thermometer on the stern and prow of a small vessel 60-m long has registered a difference of 12.3°. On the vertical plane the difference can be even greater. In a layer 16-20 m thick the temperature can vary by as much as 3° a metre. The phenomenon takes enough heat out of the Gulf Stream (about 1.5×10^{18} Cal/year) to melt all the drift ice in the Arctic in less than a year.

The warm waters lose still more heat further northwards as they progress. It is known that the Gulf Stream s temperature and power axis passes along its left, northern margin, which suffers from the contact with the cold waters all the way up. In the vicinity of the Labrador Sea there is a major counterclockwise circulation of water, caused by the left arms of all big currents—the Labrador, the North Atlantic, the Irminger, and the East Greenland. The circu-

lation, which is full of local maelstroms, also squanders much heat.

In the European Basin the cold streams of the East Greenland Current intermingle with the northern extension of the Gulf Stream system. There, too, much heat is lost because of countless maelstroms and collisions. Moreover, the west winds drive the ice fields and the cold desalinated

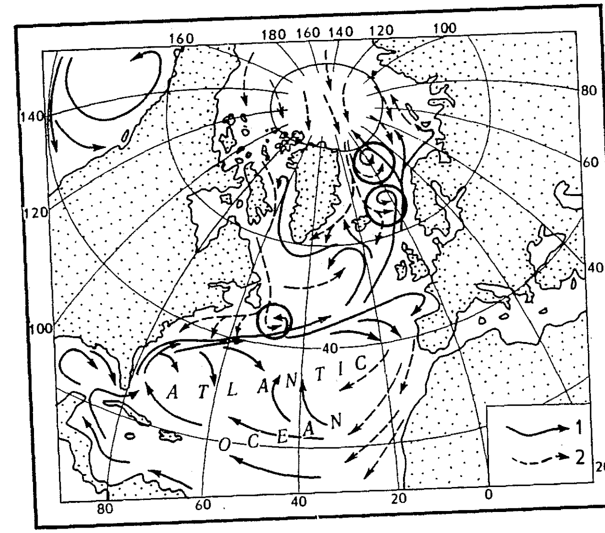


Fig. 19. Counterflow of warm and cold currents in the North Atlantic
1—warm; 2—cold

waters from the East Greenland Current towards the warm waters. The east winds, on the contrary, drive the surface waters, i.e., the warmest waters, towards the cold waters and ice. In both cases the waters mix, and the Atlantic waters lose much of their heat in the process.

The warm Irminger Current is greatly cooled in several places by the cold counterflow. We should make particular note of the Irminger's right offshoot which flows round Iceland from the west. There it enters a fork of the East Greenland Current, mixes with its left offshoot and loses itself in a whirlpool. The contact is so close that it produces

a temperature change of up to 6° per vertical metre, i.e., a greater change than at the juncture of the Gulf Stream and the Labrador Current off Newfoundland.

A good example of the chaotic movement of the waters is furnished by the perpetual currents in the northern part of the Barents Sea, where 32 stable cyclonic and anticyclonic whirlpools, including 27 which function the year round, have been registered in an area of approximately 600,000 sq km.

The incessant clashes and counterflows complicate the trajectory of the warm and cold currents. For instance, a drop of Pacific water may pass through the Chukotka Sea and the whole length of the Arctic Basin, join the East Greenland Current and enter the Atlantic. It will then follow the West Greenland Current as far as the north of Baffin Bay and turn south with the Labrador Current. From Newfoundland and onward it will ride the North Atlantic Drift, whence the Norwegian and the Spitsbergen currents will take it back to the Arctic Basin to dive under the ice and return to the Chukotka Sea. All along the journey the passing warm and cold waters will raise or lower its temperature. Naturally, this chaotic movement reduces the thermal effect of the Gulf Stream system, particularly in the higher latitudes.

In other words, the whole region northwest of the Grand Bank to Novaya Zemlya resembles a cocktail shaker which mixes the cold waters of the Arctic with the warm waters of the Atlantic.

Besides losing heat all along the way, the warm currents also dissipate their water masses, causing a further reduction in their heat content.

Consequently, only a small portion of the Gulf Stream's original heat reaches the Arctic Ocean. The current arrives there quite exhausted. At 38°N its volume amounts to 2,585,000 cu km/year. Its mean temperature at this latitude is about 20°C. But when the Gulf Stream reaches latitude 61°N and takes the name North Atlantic Drift and enters the Arctic Ocean through the Faeroe-Shetland Strait, its volume stands at 298,000 cu km and its mean temperature, 6.5°C. So at this point the current has only 12 per cent of the volume and less than 4 per cent of the heat content it had at 38°N.

The Arctic Basin only gets the leftovers. The volume is down to 135,000 cu km of water per year at 81°N and the temperature to 1.9°—the heat content is 250×10^{15} Cal. This is a far cry from the generous gift possessed by the Gulf Stream at 38°N. In fact only 5 per cent of the warm waters reach 81°N, and even then their heat content drops to less than one per cent of what it was on the latitude of New York.

C. Brooks, whose deductions we have quoted time and again, has clearly demonstrated how the counterflow of warm and cold waters robs the Gulf Stream of its heat and considerably weakens it on its northward course. He writes:

"From a study of the sea surface isotherm of the North Atlantic, we find that in January the temperature along the centre of the Gulf Stream is 71°F in latitude 30°N and 64°F in 38°N, a fall of 0.9°F per degree. From 38° to 43°N, on the other hand, temperature falls by about 22°F in only 5 degrees. Of this fall, only about 5°F can be due to the normal fall with latitude, and the remaining 17°F is due to admixture with the cold water of the Labrador Current. That is, the present January sea surface isotherm of about 32°F in 75°N, 10°E, would be replaced by one of 49°F."

That is how the cold currents prevent the warm currents from heating the Arctic to the full of their ability. Naturally, this provokes a desire to bring some order into the system of warm and cold waters and prevent the needless and unfortunate contact.

But what is to be done about the cold waters which persistently move westwards to the Atlantic, towards the warm waters? Let them go eastwards, away from the main, the Atlantic, source of heat. The cold Arctic waters should be artificially drained into the Pacific, or rather, its northern outlying region, the Bering Sea. Then, instead of the counterflow of warm and cold waters we would have a direct flow of warm waters. The warm Atlantic waters would go through the Arctic Basin into the Bering Sea and on to the Pacific Ocean; they would not turn back, as at present, into the Atlantic to obstruct the advection of heat into the Arctic.

So, the direct flow would take the following route: North

Atlantic—European and Arctic basins of the Arctic Ocean—Bering Sea—Pacific Ocean.

On the way this flow would eliminate the two basic causes which generate and nourish the drift ice in the polar latitudes: first, the cooling of the Atlantic waters in the North Atlantic and the European Basin, and second, the Arctic's low salt content of the surface waters.

But this about-face, this conversion of counterflow into direct flow, cannot be executed without a force strong enough to prevent the waters from taking the westward course again. A dam with pumping stations in the Bering Strait, affording the passage of Arctic waters into the Pacific, would serve this purpose well. The direct flow would change the composition of the circulating waters in the Arctic refrigerator. There would be no trace left of the 36,000 cu km flow of Pacific waters: the dam would block their passage. The drainage through the North European Basin and Baffin Bay into the North Atlantic would be reduced by the same volume. But a direct flow could be created by transferring 175,000 — 36,000 = 139,000 or, roughly, 140,000 cu km of water per year. Modern power engineering is equal to this job.

Why do we give such unhesitating preference to the Atlantic waters? What about the Pacific waters potential? Fridtjof Nansen, for instance, placed his hopes on the warm waters of the Kuro Shio. But he was on the wrong track. The physico-geographic conditions are against the Pacific waters (P. M. Borisov, 1962).

Firstly, the volume of the Atlantic waters is four times and their heat content ten times that of the Pacific waters.

Secondly, the northern latitudes in the Atlantic are much warmer, and its thermal equator is further north. The temperature of the upper layer of the Atlantic, i.e., the active, heat-producing layer, at 30°N is higher. As we proceed further north, the contrast grows stronger. Beyond 50°-60°N the Atlantic waters gain even greater advantages over the Pacific.

Even if we go as deep as, say, 200 metres, we should find that in the North Atlantic the isotherms 10° and 5° pass approximately 1,800 and 2,700 km, respectively, nearer the pole than in the Pacific. Lower down, at the depth of 400 metres, the Atlantic still has the upper hand.

Moreover, the Atlantic waters enter the Arctic Basin at a point 1,600 km nearer to the pole (81°N as against 66°N for the Pacific).

Another reason is that the northern part of the Pacific Ocean has a lower salt content (Fig. 18), so that the waters are of lower density. Thus, on entering the Arctic Basin they would continue to spread, at the upper desalinated level, discouraging the vertical water circulation and the utilisation of the heat of the Atlantic waters. The denser Atlantic waters, on the other hand, would travel in deep-sea channels in the Bering Strait and run southwards to the Pacific. The climate can only gain from this since it rules out cooling of the overhead air.

The Atlantic waters also heat the Atlantic winds bound for Eurasia. This heat injection would be increased if the warm waters and the warm air moved in the same direction. Besides, it has been established that the Atlantic cyclones penetrate deeper into the Arctic, and therefore, could make better use of the extra heat.

In the east, the Eurasian mainland would be walled off from the newly generated heat by the Kamchatka, Chukotka and Yakutia mountain ranges. In the west, there is no such barrier. In the first case the continent's gates would be bolted in the face of the heat radiating from the warm waters, in the second, they would be wide open.

Finally, we must take into account the nature of the Bering Strait in relation to the important part it would play in the contemplated climatic changes. The clear opening is narrow and comparatively shallow. For an equivalent thermal effect, the influx of Pacific waters would need to be much greater, which would require additional and unreasonable effort, capital and power expenditures.

To put it in a nutshell, all the factors seem to favour making use of the Atlantic waters. Proceeding from this, let us see what would happen if the Bering Strait Dam, the west-to-east water-transfer system and the direct flow of the warm Atlantic waters actually existed. What would we then see in the Arctic Basin?

Let us first examine the present make-up of the Arctic Basin's thermal balance, its sources and quantity of heat and how it disposes of its heat reserves. The calculations

Debit		Credit	
Reflected radiation	54.3	Total radiation	72.6
Effective radiation	16.8	Heat from the Atlantic waters	2.5
Heat exchange with the atmosphere	5.0	Heat from the Pacific waters	0.4
Evaporation	5.0	Heat from river waters	0.2
		Heat saved by the outdrift of ice	2.4
Total	81.1	Heat saved through the outflow of cold water	3.0
		Total	81.1

are based on the number of kilocalories absorbed by one square centimetre of surface per annum.

When the outflow of cold waters and ice from the Arctic Basin is stopped, and the basin no longer receives warm waters from the Pacific it will lose 5.8 Cal/sq cm/year (3.0 + 2.4 + 0.4).

To retain the present heat level, there must be compensation for this loss. This would have come from Atlantic waters. The heat supplied by the Atlantic waters would have to rise from 2.5 Cal/sq cm to 8.3 Cal/sq cm/year. Any additional heat would go towards melting the ice cover.

At an average temperature of minus 10°C and salt content of 10 per mill it takes 0.079 Cal to melt one gramme of ice. Taking 0.9 as the specific weight and 275 cm as the average thickness of the ice cover, we find that the specific heat consumption needed to melt the cover would be 19.5 Cal/sq cm. Since the ice mass has somewhat increased in volume during the contemporary fall in temperature, let us allow for a consumption of 21.5 Cal/sq cm.

If we set three years as the time limit for melting the ice cover, the Atlantic waters would have to provide 21.5 : 3 = 7.2 Cal/sq cm of additional heat each year. The total heat required would be 15.5 Cal/sq cm/year, that is, $15.5 \times 8.75 \times 10^6 \times 10^{10} = 1{,}360 \times 10^{15}$ Cal/year to melt the 8.75 million sq km of ice.

Do the Atlantic waters command such a reserve of heat? Yes, and considerably more. It is enough to recall that the North Atlantic Drift carries off $1{,}922 \times 10^{15}$ Cal to the Norwegian Sea every year through the Faeroe-Shetland Strait. The Arctic needs only 70 per cent of this to have all its drift ice melted in just three years.

Now we shall have to specify the volume of water that should be transferred from one ocean to the other. Calculations indicate that if we created the direct flow and stopped the cold drainage into the European Basin and Baffin Bay completely, the temperature of the Atlantic waters at the point of entry to the Arctic Basin would be 8.2°C. At the exit through the Bering Strait this temperature would have dropped to —1.6° or —1.8° (the melting point of sea ice). That would last until the obliteration of most of the drift ice. Basing our calculations on the above-mentioned temperature, we can deduce that the Atlantic waters will lose 9.8° (8.2° — (—1.6°) = 9.8°) in the Arctic Basin.

The Atlantic waters, as we pointed out, will have to carry $1{,}360 \times 10^{15}$ Cal/year into the Arctic Basin. Dividing the sum by 9.8° we get 140,000 cu km, i.e., the volume of the annual Atlantic inflow. So if we wished to destroy the ice cover in the Arctic Basin within three years, we should have to transfer exactly that volume of water from the Arctic Basin to the Pacific Ocean.

So the direct flow will help the Atlantic to supply the Arctic Basin with 140,000 cu km of water, compared with the present 135,000 cu km. The temperature at the point of entry would increase from the present 3.5° to 9.8°*. The heat content would rise from 472×10^{15} to $1{,}670 \times 10^{15}$ Cal/year. In effect the volume would hardly change, but the heat content would be trebled. The effect will be produced exclusively because of the higher temperature resulting from the disappearance of the cold counterflow from the Arctic Basin.

We set a three-year period for melting the ice on purely formal grounds, proceeding from the mathematical calculations. In practice, however, it would take longer. It will take time to convert the counterflow into the direct flow. Extra time would have to be allowed for disadvantageous anomalies, which are quite inevitable, if we remember that the calculations are based on normal conditions. And last, but not least, it would take two or, perhaps, three years of pumping before the Atlantic waters reached the necessary 8.2° at their entry into the Arctic Basin. So it

* From the approximate melting point of sea, ice i. e., —1.6 °C.

would be better to assume that we would need 4 or 5 years to melt the ice cover.

But in any event, the climate would begin to improve from the first year of pumping.

Once the drift ice is gone, the Arctic's thermal balance would be reshaped. Today the Arctic ice reflects 54.3 Cal/sq cm/year, against the 10.0 Cal/sq cm/year which would be reflected by water. In other words, the main cause of heat losses would have been eliminated.

According to our estimates, the effective radiation would remain constant at present level of 16.8 Cal/sq cm/year. There is little reason to fear a rise in radiation losses, since we know that the surface air masses will become more humid, and so prevent any increase in infrared radiation, although some researchers take the view that the radiation is bound to increase to some extent. So, to allow for this possibility let us add one-third to the original figure and estimate radiation losses at 22.6 Cal/sq cm/year. Naturally, once the basin is cleared of ice and cold waters, there would be no further heat losses on melting the ice or heating the cold waters.

Table 7

The Arctic Basin's surface thermal balances in contemporary and ice-free conditions (Cal/sq cm/year)

Components	Contemporary conditions	Ice-free conditions	Result
Debit			
Reflected radiation	54.3	10.0	44.3
Effective radiation	16.8	22.6	—5.8
Evaporation	5.0	30.0	—25.0
Heat exchange with the atmosphere	5.0	10.0	—5.0
Total	81.1	72.6	+8.5
Credit			
Total radiation	72.6	72.6	—
Sea advection	3.1	—	—3.1
Heat saved from outflow of cold waters	3.0	—	—3.0
Heat saved from outdrift of ice	2.4	—	—2.4
Total	81.1	72.6	—8.5

In establishing the heat consumed by evaporation and convective heat exchange, we shall proceed from up-to-date data collected in the northernmost ice-free zones: 30 Cal/sq cm/year on evaporation and 10 Cal/sq cm/year on convective heat exchange. Accordingly, the Ice-free conditions column in Table 7 indicates the surface thermal balance of an ice-free Arctic Basin in the absence of sea advection.

We have noted that the basin's open surface, deprived of the sea advection of heat, becomes unstable. So in order to keep the Arctic Basin ice-free, we shall have to provide it with a definite volume of artificially produced sea advection. Without going into details, specifying the volumes for each stage of warming, we shall simply note that the artificial advection (15.5 Cal/sq cm/year) is capable of quenching any cooling effect which may be engendered by the possible rise in the reflected and effective radiations.

We must mention that the calculations rule out the possibility of a regeneration of ice in the presence of sea advection. It would also be proper to cite the highly important conclusions drawn by Professor V. S. Samoilenko in 1964:

1. If the advection of heat into the Arctic Basin retained no less than half of its present level, i.e., at least 0.025 cal/sq cm per minute, there would be no natural regeneration of ice.

2. The ice sheet would inevitably regenerate if the heat advection dropped by more than a half, i.e., to less than 0.025 cal/sq cm per minute.

Taking the sea advection to be 15.5 Cal/sq cm/year, we get 0.0295 cal/sq cm per minute, or 18 per cent more than required according to Professor Samoilenko's computations. So we have every reason to expect that even if the atmospheric advection stood at zero, there would be no danger of reglaciation.

Comparing the modern and ice-free balances, we find that the net heat gain from radiation factors totals 38.5 Cal/sq cm/year. Most of it (30 Cal/sq cm/year) will be consumed by the sixfold rise in evaporation and doubled warming of the atmosphere, the remaining 8.5 Cal/sq cm/year will compensate the credit entries, which will eventually disappear, of the contemporary thermal balance.

The extra heat consumption by evaporation and atmospheric warming fits in with our plans. The heated air will spread over the continents and warm them. The heat consumed by evaporation will be compensated in two ways. First, the continents will get extra moisture, and, second, they will get back all the heat lost during the condensation of vapour. And the cooling of the Earth surface in the higher and moderate latitudes will be retarded.

A GULF STREAM IN THE ARCTIC BASIN

> The distribution of density and the density of sea water in general depend more on temperature than on salt content.
>
> *Y. M. Shokalsky*

And so we have attempted to show that a Polar Gulf Stream project is a feasible undertaking. However, some scientists contend that the direct flow would not bring the Atlantic waters up to the surface, and, since they are heavier than the surface Arctic waters, they would continue to sink into the basin's deep zone. Others claim that the transfer of water from the Chukotka Sea to the Bering Sea would prompt the cold waters in the Arctic Basin to float up, cancelling out the thermal effect of the direct flow. Others fear that the cold Arctic waters would reinforce the cold Kamchatka Current and, then the cold Oya Shio Current. So, instead of becoming warmer, the Soviet Pacific coast and the Japanese islands would turn colder. In essence, all these arguments boil down to this: It is impossible to create a Polar Gulf Stream, but even if it were possible, it would not be expedient. We need quantitative data to refute all these arguments. Let us examine them in greater detail.

First of all, would the Polar Gulf Stream take to the surface on its way across the Arctic Basin?

We have already pointed out that the greater the influx of the Atlantic waters the higher is the temperature and salt content in the Arctic Basin. The waters sink into the basin's deep zone. This is what creates the fear that a direct flow would also fail to stop the process. However, scrupulous analyses have proved that this fear is groundless.

It has been established that a sufficiently high temperature not only delays a rise in density, which, if we remem-

ber, depends on an increase in salt content, but actually reduces it. This has been proved conclusively by a comparison in observations in 1894-1896 by Fridtjof Nansen, on the *Fram*, and in 1898, by S. O. Makarov, on the *Yermak*, with observations taken many years later. In Nansen's and Makarov's time, the upper margin of the Atlantic water layer in the north of the Barents Sea passed at the depth of nearly 200 metres. By 1933, after a few years of heavy influx of warm Atlantic waters into the Arctic Basin, the layer, instead of going down, had risen 130-150 metres and reached the 70-50-m marks.

In 1895 Nansen's expedition discovered an upper warm layer at the depth of 200 metres in a place situated north of the Kara Sea. Forty years later, in 1935, the icebreaker *Sadko*, cruising in about the same area, found that the layer had risen to the 110-m mark.

The rising temperature, as we see, had pushed the warm waters closer to the surface. True, we must concede that in the span of 40 years the changes could hardly have been that simple. Rises were probably followed by drops, and vice versa. But when the maximum and mean temperatures of the Atlantic waters were at their lowest, the upper margin always descended. Irrefutable proof of this can be obtained by comparing the hydrological data for 1931, the year of maximum temperatures, with the data for subsequent years.

At present we have the counterflow, and as soon as the temperature of the Atlantic waters rises, they tend to come up to the surface. But, as we know, the process is obstructed by the cold desalinated waters which continually move from east to west and replenish the cold upper layer.

The west-to-east transfer, once realised, would remove the waters of the uppermost (the lightest) layer. The dam in the Bering Strait would block the northward passage of 36,000 cu km/year of Pacific waters—the major cause of the desalination. So the two main causes which prevent the warm Atlantic waters from rising to the surface would be gone.

With water pumped from the Chukotka Sea to the Bering Sea, the Atlantic waters would be stimulated to come up to the surface.

We must observe that by pumping 140,000 cu km of water a year from the Arctic into the Bering Sea we would be lowering the water level in the Arctic Basin by 16 metres per annum. This would only affect the upper layer. Quickly losing in bulk, it would no longer be able to prevent the Atlantic waters from rising to the surface. Naturally, the speed of the Atlantic waters' upward movement would be in inverse proportion to the thickness of the upper layer.

The expected pattern (immediate surfacing of warm Atlantic waters as soon as the cold desalinated waters weaken their thrust from north and east) is not only substantiated by calculations, but also by long observations of water régimes in the polar latitudes. For example, it has been established that when the pressure of the cold East Greenland Current abates the warm Atlantic waters increase their thrust in the Denmark Strait. So, instead of sinking below the East Greenland Current's offshoot of light waters, as they usually do in the neighbourhood of North Iceland, the warm Irminger waters stay on the surface and rush eastwards and northeastwards. Usually, the cold Labrador Current prevails in the vicinity of the Grand Bank, but when its thrust subsides, the warm Atlantic waters displace these waters and rise to the surface.

Some researchers argue that it is uncertain how long it would take the Atlantic waters to reach the surface. To clarify this point, we must examine how the Chukotka-Bering flow would eventually affect the temperature, salt content and density. Leaving alone the sophisticated and intricate computations, we shall merely state the final results, indicating their source.

At the entry to the Arctic Basin, the temperature of the Atlantic waters, we said, would rise from 1.9° to 8.2°C. The rate at which the temperature would climb can be deduced from the speed of the Gulf Stream from Cape Hatteras to Newfoundland and the Faeroe-Shetland Strait, and on to the point where they sink beneath the desalinated layer of Arctic waters. According to calculations, the temperature would rise at the following rate: from 1.9° to 4.5° in the second year; 4.5° to 7°, in the third year, and 7° to 9°C, in the fourth year. Since there will not be any need for a further rise, the temperature could easily be stabilised by regulating the volume of incoming Atlantic waters.

Naturally, the Atlantic waters would become more saline at the entrance to the Arctic Basin once the counterflow of desalinated Arctic waters stops completely. However, the maximum salt content will not exceed 35.4-35.5 per mill as against the present 34.95 per mill. This is corroborated by the information in the Soviet Sea Atlas of the Salt Content of North Atlantic Waters and by the data referring to the waters' desalination by atmospheric precipitation and shore drainage north of 45°. Basing ourselves on the data, and taking into account the speed of the Gulf Stream, we may expect the salt content of the waters at the entrance to the Arctic Basin to rise at the following rate: 35.15 per mill, in the second year; 35.25 per mill, in the third; 35.30 per mill, in the fourth; and 35.35 per mill, in the fifth year. There would be a very slight rise in salt content after the fifth year, but it would not exceed 35.4 per mill after the tenth year.

The changes in temperature and salt content will affect the density as shown in Table 8.

Table 8

Changes of temperature, salt content, density and depth of the layer of Atlantic water to be brought about by the Bering Dam project (for position 80°N, 8°-10°E)

Year of pumping	Depth of water layer, m	Temperature, °C	Salt content ‰	Density, σt
Second	150-350	4.5	35.15	1.027.86
Third	100-300	7.0	35.25	1.027.65
Fourth	50-200	9.0	35.30	1.027.38
Fifth	0-150	9.5	35.35	1.027.33
Tenth and up	0-150	10.0	35.40	1.027.28

To keep the Atlantic waters at their present depths in the Arctic Basin, given the temperatures indicated in Table 8, the salt content should be: 35.30 per mill after the first year of pumping; 35.65 per mill after the second; 36.03 per mill after the third; 36.17 per mill after the fifth, and 36.26 per mill after the tenth year. But, as we have already pointed out, we cannot expect a salt content of 35.5 per mill, much less 36.0 per mill.

It is clear that the Atlantic waters would not be threatened by a greater density. Moreover, because of the higher temperature, their density will even be reduced. So the Atlantic waters will certainly flow through the Arctic Basin's surface layer.

Earlier we said that some researchers doubted the feasibility of the Polar Gulf Stream project. So we must answer one more question: will the inter-oceanic flow involve the deep waters too? No, it will not, because the waters in the Arctic Basin are of unequal density (see Table 6).

The deep waters, particularly the bottom waters, which lie under the warm Atlantic waters in the Arctic Basin are among the heaviest in the World Ocean. Their great density is due to high salt content and low temperature. They and the cold Antarctic waters cool the deep waters under the equator. We know that waters of high density sink but never rise. The American oceanologist G. E. R. Deacon found that the disturbing forces which cause the vertical intermixing of waters, are generally not strong enough to overcome even the weak density gradients. Here are some corroborative examples.

The prevailing trade winds near the northwestern coast of Africa drive the surface waters away from land. They are supplanted by waters rising from 100-200 or, at most, 300 metres. The ocean surface there, we should note, has an incline of 4 cm per 1,000 km. A similar phenomenon can be observed at 35°-41°N off the Californian coast.

The incline in the Arctic Basin, when the flow is set in motion, will not exceed 8-10 cm. So, according to calculations, the specific incline would be less than the incline off the African and Californian shorelines and there is no danger of waters which now travel 200 to 300 m below sea level would rise to the surface.

It should be said that a moderate attraction of water from 200-300 metres or, even better, from 500-600 metres, would even be desirable as this would raise the temperature over the Chukotka Sea shelf and accelerate the melting of the ice which would be accumulating there. It is a pity, that there is absolutely no likelihood of this for the following reasons:

In 1960, Y. G. Ryzhkov and, later, other researchers found theoretical proofs that deep waters are bound to

rise if the surface waters are removed. They discovered an interdependence between vertical stability of the surface layer and the depth from which the waters rise under the effect of the driving wind.

Fig. 20 shows this interdependence in graphic form. When the stability $E \times 10^8 = 2{,}000\text{-}3{,}000$, the water rises from a depth of 30-50 metres, but when $E \times 10^8 = 500$, it rises from the depth of 200-250 metres, i.e., the smaller the vertical stability of the surface waters the

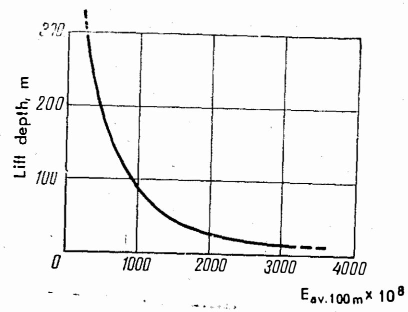


Fig. 20. The dependence of the rise of deep waters on the vertical stability of the surface waters (Y. G. Ryzhkov, 1960)

greater is the depth from which the deep waters rise. This is in full accord with Y. G. Ryzhkov's conclusion that "it is absolutely clear that the maximum rise of deep waters occurs only in places of low vertical stability; in areas of stable stratification, the rise does not exceed 40 metres" (1960).

The conclusions drawn by the other researchers were similar.

If we glanced at the chart of the hydrological cross-sections of the Arctic Basin, we would find it is covered almost entirely by surface waters of high vertical stability ($E \times 10^8 = 2{,}000$ and up) and that the extremely limited areas of low vertical stability ($E \times 10^8 = 500$) are confined to the neighbourhood of Franz Josef Land. It follows that only subsurface waters, from 30-40 metres down, would rise to the surface; the rise of deep waters or even of warm Atlantic waters is impossible.

This conclusion is also warranted by on-the-spot observations. The backflow into the Atlantic, involving 175,000 cu km/year of the basin's surface waters, runs from east to west. We have noted that the surface layer moves fastest.

Lower down, the movement gradually slows down and dies away to nothing at the depth of 100-200 metres, i.e., the waters lying beneath this mark take no part in the drainage. So, far from being involved in the surface, east-to-west, drainage, the warm Atlantic waters move in the opposite direction, from west to east, almost along the entire length of the Arctic Basin.

If the Chukotka-Bering transfer were set in motion, the Arctic-Chukotka drainage would largely involve surface waters and they would attain the maximum speed. The layer 100-200 metres down, i.e., the practically motionless water, would also start to move eastwards, though at a much lower speed, because of the Bering Strait Dam's suction force.

But the high vertical stability would prevent the deep masses from reaching the pumps. It would take an enormous amount of energy to overcome this: to raise one cubic metre of water from the layer occupied by the intermediate lower water mass, it would be necessary to apply a force of 3,100 kgm: $(1{,}028.09 - 1{,}024.50) \times (630 + 172 + 64)$.

The deep waters in the Arctic Basin have no such energy potential.

In passing, we should note that the dam will border on the huge area of shallows (roughly, 1,000 km in radius) of the East Siberian and Chukotka seas which are not deeper than 200 metres anywhere. It is a happy accident which would keep all but the surface waters out of the pumping systems in the Bering Strait.

The Chukotka-Bering flow and the Polar Gulf Stream would substantially alter the stratification and the dynamics of the water masses in the Arctic Basin.

First of all, the basin would lose its light surface waters, and then the intermediate upper waters. The former amounts to 321,000 cu km, and the latter, 864,000 cu km. At a rate of 140,000 cu km/year, it would take, in theory, two years to drain the surface layer, and six for the intermediate layer.

Since both layers would be replaced by warm Atlantic waters, we have every reason to expect a considerable simplification in the stratification of the basin's waters by the end of the eighth year. There would only be three, instead of the present five, layers: the Atlantic, the inter-

mediate lower and the bottom layers. The Atlantic and intermediate lower layers would become much thicker; the bottom layer would be contracted; and, finally, the Arctic surface and upper intermediate waters would disappear.

We have set an eight-year time limit on purely theoretical grounds. Actually, the changes would begin earlier. Some of the upper intermediate waters would be carried off into the European Basin and into Baffin Bay, and the remainder, when all the ice is melted and there is nothing to protect them from the winds, would mix with the underlying Atlantic waters. The winds could mix the waters to the depth of 50-100 metres.

Since the influx of saline Atlantic waters will be intensified, we might expect a gradual salination of the Arctic Basin. In practice, however, this process would be almost imperceptible because the direct flow would carry off the bulk of the Atlantic waters into the Pacific Ocean so swiftly that they would have little time to mix thoroughly enough with the deep waters to salinate them. And anyway the main source of desalination, the shore drainage, would still be there, even though its influence would only be felt in the offshore zone.

The dynamics of the waters would also undergo a serious change. The bulk of the warm Atlantic surface waters would move from west to east, closely following the big arcs in the general direction of the Bering Strait. But the Coriolis force would press their midstream closer to Eurasia's northern coasts, which would be a contributory factor to their warming.

It would take the Atlantic waters about two and a half years to pass from Spitsbergen to the Chukotka Sea, as against five at present.

A GULF STREAM IN THE PACIFIC OCEAN

> In winter the Gulf Stream's impact affects a much greater area than we assume; its influence extends to the entire northern half of the Eurasian continent ... a rise in its temperature might even affect the eastern coast of Asia.
>
> *V. B. Shostakovich*

The Pacific Ocean probably presents the most formidable argument against the Polar Gulf Stream idea. What if the waters transferred from the Arctic Basin to the Pacific Ocean were to bring cold to the Soviet Pacific coast and the Japanese islands? We must point out that such misgivings are unfounded.

The North Atlantic waters have a higher salt content than the waters of the north of the Pacific Ocean (see Fig. 18). Given equal temperature, the inflowing Atlantic waters, being denser, would inevitably sink below the local Pacific waters. Moreover, the colder the waters, the more surely they will readily submerge. So they would have no chance to influence the local climate.

This all sounds very convincing, but that is not enough to overrule the objections.

The fact remains that in the first two or three years we would not be transferring Atlantic, but Arctic surface waters, i.e., the coldest and lightest (because of their low salt content) waters. But is there any danger that they may cool Asia's eastern coasts? Before answering the question, we must study the climate and its formation along Asia's northeastern coasts in greater detail.

The powerful Asian anticyclone which develops in the heart of Asia during the cold season drives out masses of dry and cold air (winter monsoons) from the mainland's central regions. The air rises as high up as four kilometres, and so the watershed mountain ranges are unable to isolate the western shores of the Pacific Ocean from the impact

of the winter monsoon. The monsoon speeds ahead very swiftly since its general direction coincides with the Earth's west-to-east drift of air masses in those latitudes. This influx of cold air is so steady and strong that even the ocean cannot help to soften the climate on the mainland.

The cold air penetrates down into the subtropical latitudes and cools the western shore of the Yellow Sea. The mean January temperature in Shanghai and Hangchow is —4°C and lower, compared with +12° to 14° in Kuwait, Alexandria, Cairo and Madeira at approximately the same latitudes.

In summer, when the Pacific anticyclone gathers force, intensive heating creates a low pressure zone over Asia. As a result, humid sea air masses (the summer monsoon) move over the continent. They penetrate as far inland as the Yablonovy, the Stanovoi and other mountain ranges. That is the reason for the wet summers in the Kuriles. And in Kamchatka the summer is cold as well as damp, because the peninsula is surrounded by the cold Okhotsk and Bering seas. The climate in North Japan is greatly influenced by the cold Oya Shio Current, which carries mists that screen off the solar radiation. The Oya Shio's adverse impact is strongest in years when there has been a lot of winter ice in the Okhotsk and Bering seas. In those winters the ice masses drift into the Oya Shio Current causing low summer temperatures in North Japan which damages the rice harvest.

Year after year, the steady, vigorous winter monsoons cool Asia's eastern seaboard from Chukotka right down to the tropical zone. Snowfalls don't occur at such low latitudes anywhere else in the world. Sweeping across the outlying seas, from the Bering to the Yellow, the winter monsoon turns them, particularly the northern seas, into gigantic deposits of ice and extremely cold water. Because of the proximity of Oimyakon, the pole of cold, the temperature in the seas drops below zero even at depths of 1,000 metres and more. The reserves of winter cold, accumulated by the seas, are big enough to cool the atmosphere in warm seasons and worsen the climate in the adjacent territories.

The winter monsoon, which owes its origin to the freeze-up in Central Asia and the formation of the Asian and Polar anticyclones, is not an enduring phenomenon. True,

when fed by the cold air masses from the north, the Asian anticyclone gains force. But as soon as the cyclones cross the Taimyr Peninsula and reach Lake Baikal, the anticyclone loses power and dies away and gives way to active cyclonic processes.

Incidentally, in the past, when the temperature of the waters in the North Atlantic was higher and the Arctic got warmer, the Asian anticyclone lost much of its force. Lake Baikal became warmer, while Mongolia had better conditions for the growth of forests.

When the anticyclone fades, it also gets warmer in the northwest Pacific. It is here, where the biggest continent meets the greatest ocean, that we can observe the greatest fluctuations in the temperature of the surface waters of the World Ocean. This is largely because of the strong dry winter winds.

The sharp temperature contrasts between the continent and the ocean reinforce the winter monsoon. That, in turn, causes early freezing. The artificial transfer of waters would give rise to the opposite effect: a gradual elimination of temperature contrasts between the regions of Asian maximum and Aleutian minimum. The ice would come much later, and there would be less of it, so the northwest of the Pacific would be warmer. For that reason, the warming in the North Atlantic and the pre-Atlantic sector of the Arctic will inevitably be accompanied by a similar warming in the northwest of the Pacific.

That these processes were simultaneous was discovered long ago. Back in 1924, the First USSR Hydrological Congress pointed out that the conditions prevailing in the Gulf Stream had a direct bearing on the general character of the winter weather, both in northwest Europe and in large parts of Asia.

In 1955 K. P. Pogosyan concluded from the results of aerological observations that the warm damp air masses, which advance inland from the Atlantic Ocean on a vertical front of over 5 kilometres, heat not only Europe, but also a large part of North Asia all the way to Yakutia. The heat is brought overland and across the Northern seas.

The phenomenon was corroborated by oceanographic observations. In 1955 N. N. Zubov noted: "In four or five years' time, the anomaly of temperatures of Atlantic waters

to the northwest of Spitsbergen is bound to have some effect in the Bering Strait."

Looking back on the history of world climate, we shall find clear evidence of this simultaneous process and simplicity both in the near and distant past.

Up to now, in arguing our point, we have been dealing with the current situation when there are no effluent waters (as we will for brevity's sake, call the waters to be pumped out of the Arctic Basin through the Bering Strait) which shall be cooling the Pacific waters.

To understand the contemplated régime for the Pacific waters, we must first see how the temperature and salt content of the effluent waters will be affected by their passage through the Arctic Basin.

And we must examine the oceanographic characteristics of the northwest Pacific and the Far Eastern seas carefully, to predict their reaction to the inflow of effluent waters and also the changes within their deep layers after each consecutive year of pumping.

The effluent waters would come into the Bering Sea directly from the Chukotka Sea, whose waters hardly differ from the waters in the central regions of the Arctic Basin. So we would not be wrong to assume that after the first year of pumping the effluent waters would have the same parameters as the surface waters in the heart of the Arctic Basin: temperature, —1.7°, and salt content, 30.00 per mill.

The second year of pumping would involve the intermediate upper layer which, as we know, is more saline than the surface water. In the third and fourth years of pumping, the effluent waters would be made up entirely of the intermediate upper water, and so the temperature and salt content would be considerably higher. In the fifth and sixth years there would be no ice left in the Arctic, the clear water would readily absorb solar radiation and so the temperature of the effluent waters would rise above zero.

Fig. 21 shows the expected changes in the characteristics of the effluent waters after they leave the Chukotka Sea.

The Bering Sea will be the first to receive the effluent waters after they pass the Bering Strait. It is a huge sea, its area and volume are more than a quarter the size of the Arctic Basin. The cold spells there are long and rigorous.

Its physical and geographic conditions give us reason to regard it as a giant mixing machine which would completely alter the nature of the effluent waters on their way to the Pacific Ocean.

How would that happen?

The Bering Sea is replenished by 193,000 cu km of Pacific waters a year. The effluent waters, once the pumping begins, will hold back the incoming Pacific waters to some extent

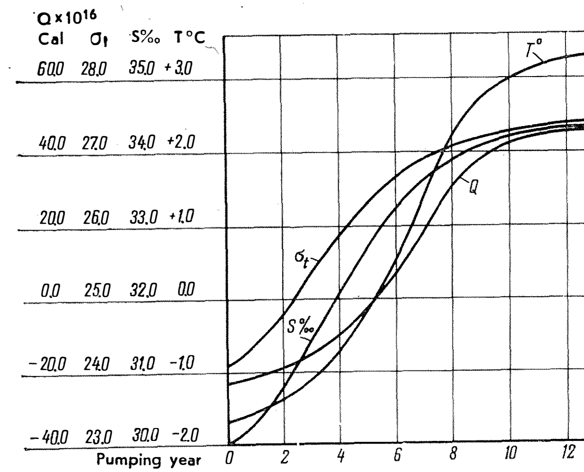


Fig. 21. Expected changes in temperature, salt content, density and heat content of waters flowing through the Bering Strait at a rate of 140,000 cu km/year T°C—temperature; S⁰/₀₀—salt content; σ_t — density; Q—heat content, Cal

and reduce the volume to 150,000 cu km/year. We will ignore the precipitation (1,300 cu km), the land drainage (650 cu km), and losses from evaporation (700 cu km) since their role in the overall water balance is insignificant.

So, the Bering Sea will have the following water balance: 140,000 cu km/year of water from the Arctic Basin, and 150,000 cu km of water from the Pacific Ocean. This mass of water would become part of the Kamchatka Current which would leave the Bering Sea by way of the Kamchatka Strait.

In theory, the effluent waters would be diluted by waters from the Bering Sea in the ratio of one to one. The bulk of the Bering Sea's surface waters is involved in a closed circular current. So it is reasonable to expect the effluent waters to be drawn into this circuit, so that less than 50 per cent of their volume would be taken away by the Kamchatka Current.

If we were to study the Bering Sea's vertical plane, i.e., the stratification of its water masses, we would find that it is very similar to the sub-Arctic structure. The intermediate layer, as in the Arctic, is cold, does not vanish in summer, and lies on top of relatively warm waters.

The upper water layer in the northern and western regions of the Bering Sea is up to 150 metres thick; it slopes up in a wedge towards the south and southeast where it meets the Pacific waters. In late winter and early spring the layer's temperature in the vertical plane falls below zero (about —1.5°, —1.7°). In late summer, radiation heat raises the temperature to 6° or 7° above zero over the entire surface.

In summer, the warming stabilises the upper water mass. It becomes unstable in winter when the sea's northern and western regions are covered with ice, and the water surface, even far from the edge of ice, is subjected to vigorous cooling. By intermixing with the lower layers the upper Bering Sea water mass transforms into the intermediate layer.

So, the intermediate water mass owes its origin to the upper mass. In very cold winters, its temperature, even as far down as 400 metres, falls to a very low level. And further south, the cold, naturally, cannot penetrate so deep. The temperature and salt content are quite stable, but to the southeast the temperature increases from —1.7° to +4°, and the salt content from 33.7 per mill to 34.3 per mill.

The Pacific water mass lies more than 250-400 metres below sea level. Its temperature is always slightly below 4°, dropping to 1.5° or 1.7° nearer the bottom. The salt content is between 34.3 and 34.8 per mill.

The warm Pacific waters enter the Bering Sea through the straits in the Aleutian chain. Most of the waters pass through the Blizhny Strait which separates the chain from the Komandorskiye Islands in the west, closer to the Asian mainland. When it gets there, the warm Pacific Current

turns to the right and circulates past the American shore. Near Saint Lawrence Island its offshots pass through the Spanberg and Chirikov straits onwards to the Chukotka Sea. But the main stream turns west, and then, south. Having been cooled on their way to the north of the Bering Sea, the Pacific waters return south as the cold Kamchatka Current, which passes the east coast of Kamchatka towards the Kamchatka Strait, but, at the very entrance to the Pacific Ocean sends out a separate cold arm, the Bering Current. Unlike the main stream of the Kamchatka Current, the branch current is in no hurry to get back to the Pacific Ocean; going eastwards, it joins the warm Pacific Current at 170°E, closing the cyclonic circulation. During the rotation, the waters mix swiftly and constantly so that the Pacific water undergoes a considerable change. The cyclonic circulation grows stronger in winter and subsides in summer, but it always remains the dominant sea current in the region.

When the effluent waters enter the Bering Sea, the Coriolis force would propell them to the west, closer to Asia's mainland, towards Cape Navarin. There they would mix with and join the Kamchatka Current. In principle, the effluent waters would not affect the circulation of waters in the Bering Sea, firstly, because the sea would no longer be wasting waters on feeding the Chukotka Sea through the Bering Strait (which would be blocked by the dam), and secondly, because the sea would get a "gift" of Arctic waters, pumped out of the Chukotka Sea into the Bering Sea. So the advantage would be twofold. The Bering Current would gain in strength, particularly in winter when the northwesterly winds are strong and stable. That would all cause quite intensive mixing of the Arctic and Bering Sea waters.

Now we are almost ready to answer the main question: is there any danger that the effluent waters, after mixing thoroughly with the Pacific waters, could cool the East Asian seas and coasts?

Before answering, we must first look at a number of relevant factors: With what heat would the Bering Sea meet the Arctic cold? How would the effluent waters change the thermal régime of the Bering Sea? Would the effluent waters consume too much heat? Would they lower the

temperature? Could they worsen the normal conditions?

The present heat balance of the Bering Sea's surface can be seen from the following indices (Cal/sq cm/year):

Debit		Credit	
Effective radiation	33.4	Total radiation	61.7
Evaporation	42.2	Condensation	1.0
Melting of ice	2.3	Glaciation	2.3
Heat exchange with the atmosphere	17.5	Heat exchange with the atmosphere	1.7
Total	95.4	Total	66.7
Balance	—28.7		

As we see, the Bering Sea wastes the greater part of its heat on effective radiation (33.4 Cal/sq cm/year) and evaporation (42.2 Cal/sq cm/year).

If we examined how the debit is distributed through the seasons, we would find that in summer (May-August) the effective radiation takes 8.6 Cal/sq cm, in winter (November-February), 13.0 Cal/sq cm; and evaporation, 2.2 Cal/sq cm in summer, and 23.2 Cal/sq cm in winter.

The heavy losses in winter are due to the dry cold air which is forced over the sea's surface by the Asian anticyclone, the Earth's west-to-east atmospheric current, and the cold air masses from the north which originate over the perennial pack ice in the Arctic Basin.

So the sea's surface has a negative balance. The Bering Sea loses more heat than it gains. The deficit comes up to 28.7 Cal/sq cm/year, i.e., to a total of 66×10^{16} Cal/year. But the deficit is compensated by the sea advection of heat from the warm Pacific Current.

If we divide the volume of heat over the volume of water which brought it, we shall find that the Pacific waters lose 4.4° ($66 \times 10^{19} : 15 \times 10^{19}$) in the Bering Sea. According to available data, the mean annual temperature of Pacific waters is 6.0°C at the point of entrance to the Bering Sea and 1.5° at the point of exit.

Now that we know the Bering Sea heat balance, we can predict the effect of the effluent waters.

In the first year of pumping (the effluent waters would be coldest then), they would cause a heat loss of $23.8 \times \times 10^{19}$ Cal. In the following years the influx of cold would

die out, and from the sixth year the effluent waters will be coming in at positive temperatures.

The curves in Fig. 22 show the expected year-by-year changes in the waters of the Kamchatka Current when they begin to mix with the effluent waters. It must be noted that the data in the diagram may err on the cold side: no account is taken of the beneficial atmospheric processes over the Bering Sea. From the very first year of pumping, the atmospheric conditions would begin to improve because

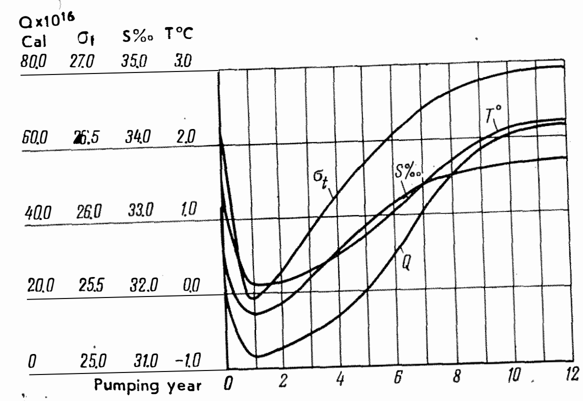


Fig. 22. Expected changes in temperature, salt content, density and heat content of the waters of the Kamchatka Current (transformed by effluent waters) at the exit from the Bering Sea

T°C—temperature; $S^0/_{00}$ —salt content; σ_t—density; Q—heat content, Cal

ice in the Arctic Basin would be shrinking at a rate of 20 per cent per annum; so not only the waters, but the air, too, will be accumulating heat. However, since this is extremely complicated to calculate, it is hard to predict the results. In the circumstances, it is better to proceed from reliable, though understated data. But even so, we can see that in the first year of pumping, the temperature of the Kamchatka Current would drop from 1.5° to 0.1° i.e., by no more than 1.4°. Since this is no more than the normal variation between one year and another in the Kamchatka Current, there is no reason to fear drastic climatic changes.

The 1.4° drop in temperature means that in the first year the Bering Sea will lose a total of 19.6×10^{16} Cal, or 8.4 Cal/sq cm. It is not much, as compared with the figures given on the preceding pages: a mere 8.8 per cent of the

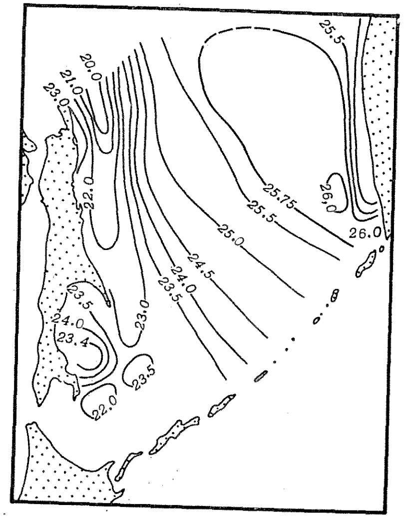


Fig. 23. Isopycnic lines of surface waters in the Sea of Okhotsk in July-August (from Japanese sources cited by A. K. Leonov, 1960)

total heat losses and only 29 per cent of the heat brought by the Pacific waters.

Besides, the cooling would only last for one year. After that, the temperature would begin to rise. By the end of the seventh year it would be back at its present level, and, by the beginning of the eighth year, higher.

We must stress again that these calculations do not take the favourable influence of the improved thermal régime in the Atlantic and the pre-Atlantic sectors of the Arctic Ocean into account. The melting of the ice would inevitably weaken the Arctic and the Asian anticyclones. Their detrimental effect would wear out gradually. As a result, the effluent waters would cool the Bering Sea's northwestern area during the first year. It is doubtful whether this cooling would even last into the second year. By the third year it would have ceased altogether.

Let us see what would happen to the effluent waters further in the southwest and how they would interact with

the waters of the Sea of Okhotsk. The latter is a very cold sea, its hydrological régime hardly differing from the Arctic seas. This is not surprising, since the Sea of Okhotsk lies 500 kilometres from the pole of cold (Oimyakon) and a little more than that from the centre of the Asian anticyclone. The coasts of the Arctic seas (the Laptev and the East Siberian seas) are two times as far from the pole of cold.

The sea's water balance is as follows (in thous. cu. km. p.a.):

Debit		Credit	
Drainage into the Pacific Ocean	160.0	Inflow from the Pacific Ocean	144.0
Evaporation	0.5	Inflow from the Sea of Japan	15.0
Total	160.5	Mainland drainage	0.6
		Precipitation	0.9
		Total	160.5

The fact that the mainland drainage and precipitation come to three times the evaporation is very important. This greatly contributes to the desalination of the upper layer (Fig. 23). Thus, the waters of the greater part of the Sea of Okhotsk, particularly those which feed the cold Oya Shio Current through the southern straits of the Kurile Archipelago, sometimes have a lower density than the Arctic surface waters. This has a negative impact on the thermal régime of the surrounding land.

In winter, three-quarters of the Sea of Okhotsk are covered with ice. In different regions, the temperature of the surface water varies from —1.8° to 2° in winter, and from —1.5° to 15° in summer. In summer, the upper layer only warms up to the depth of 30-75 metres. It rests on the cold and relatively thick intermediate layer which goes down 200-400 metres where it saddles the intermediate lower water mass with the annual temperature fluctuations (depending on location) of —1.7° to 2.8°. The deep Pacific water mass, which passes beneath the intermediate layer, lies 1,000-1,300 metres below. Its temperature varies from 1.8° to 2.3°.

In the littoral zone the waters have a salt content of 30 per mill and less. The salt content increases from 32.8 per mill on the surface, 33.2-34.5 per mill in the inter-

mediate layer, to 34.4-34.7 per mill in the deep Pacific layer.

The Sea of Okhotsk, just as the Bering Sea, loses more heat than it gains. Here, too, the wastage is caused by effective radiation and evaporation. Here, too, the blame rests with the cold dry air masses of the Asian anticyclone, the west-to-east atmospheric drift and the air masses driven out of the Arctic. The heat deficit adds up to 26 Cal/sq cm/year. Multiplying the figure by 1,590,000 sq km (the sea's area), we find that the overall deficit amounts to 41.5×10^{16} Cal/year which is made good by the advection of heat from the Pacific.

But the thermal régime in the Sea of Okhotsk is distinguished by relatively high summer temperatures in the northern straits of the Kurile Archipelago. The southwestern area, on the other hand, is more cold. This is because the warm Pacific waters enter through the northern straits and leave, after giving up their heat, through the southern. So it is no accident that in the northern part of the generally cold Sea of Okhotsk one finds heat-loving fauna.

Girding the Sea of Okhotsk as with a giant necklace, the Kurile Islands separate it from the Pacific in exactly the same way as the Aleutians separate the Bering Sea from the Pacific Ocean. Through the Kurile straits the Sea of Okhotsk exchanges broad belts of water with the Pacific Ocean. In the Sea of Okhotsk the exchange proceeds vigorously, the waters mix thoroughly and swiftly.

The Pacific waters do not move northwards in a single powerful current, as in the Bering Sea, but in small separate streams and local circulations of varying force. Having passed the Kamchatka coast, the right offshoots detour round the northern gulfs and then, joining the left streams, skirt Iona Island from the north. The Pacific waters draw the desalinated waters of the Sakhalin Gulf into the resulting cyclonic circulation. All these waters give birth to the cold North Okhotsk Current which passes along the eastern coast of Sakhalin towards the southern Kurile straits. Once through the straits, the North Okhotsk Current joins the Kurile Current (Oya Shio). Being much lighter, it flows over the Kurile Current, and makes it much colder. The Oya Shio is replenished mostly by the cold desalinated waters from the Sea of Okhotsk. Consequently, in warm seasons, the waters of the northeast Pacific Ocean around the southern

Kurile islands and the northern islands of Japan are cooled more by the waters from the Sea of Okhotsk (which lies further south, but is nearer to the pole of cold) than by the waters from the Bering Sea (which lies further north).

On leaving the Sea of Okhotsk, the North Okhotsk Current enters the northwestern area of the Pacific Ocean and moves towards the eastern coasts of the Japanese islands. This is where the subtropical and sub-Arctic water masses drive headlong into one another.

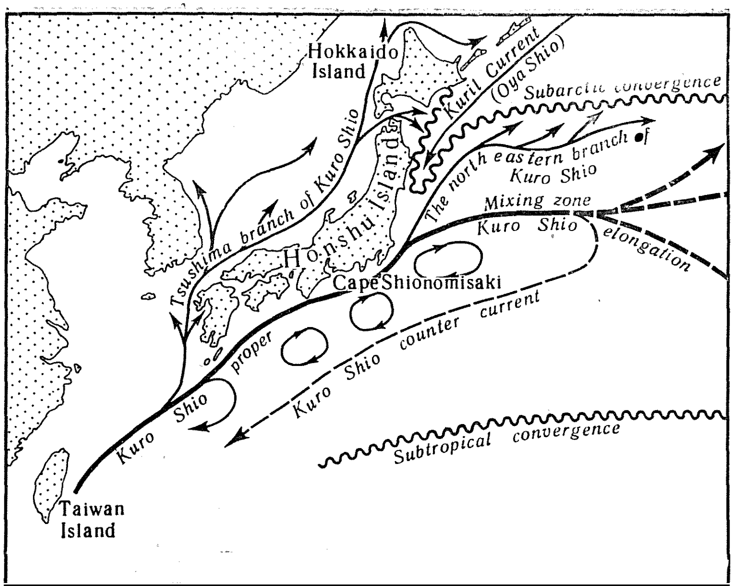
When estimating in what degree the effluent waters would be stripping the Pacific's northwestern area of its heat, we would do well to remember that not all the waters of the Kamchatka Current reach the Japanese islands. They are partly dissipated by the weak southeastern and eastern currents. A proportion of the effluent waters will inevitably be absorbed by the cyclonic circulations in the northeastern part of the Pacific Ocean. Since the effluent waters would, in the final count, be consumed by sub-Arctic and then by subtropical water masses, we should briefly examine the principal characteristics of these.

The subtropical water mass is formed by waters which come in from the southwest. The stream is formed by the warm Kuro Shio Current. The Japanese researcher Masuzawa claims that actually the Kuro Shio itself is a rather narrow stream which moves at the speed of 20 cm per second and more. He calls the remaining water mass "the region of eastern drift".

Cape Shiono misaki, at the southern tip of Honshu (the main island of Japan) serves, so to speak, as a dividing line in this south-to-north water drift.

In the north, beyond 34-35°N the subtropical and sub-Arctic water masses make direct contact. The effluent waters would, presumably, also make contact with the subtropical waters there. The subtropical current reaches Cape Shiono misaki unchanged. Here are its characteristics at this stage:

	Region of Eastern Drift	Kuro Shio
Width, naut. miles	126	90
Cross-sectional area, 10^6 sq m	207	79
Mean temperature, °C	12.6	16.5
Average speed, cm/sec	24.5	49.2
Size of drift, 10^6 cu m/sec	48.3	37.9



F i g. 24. Schematic diagram of currents in the Kuro Shio system according to Masuzawa (cited by V. V. Leontyeva, 1961)

The diagram of the Pacific's northeastern part (Fig. 24) shows the Kuro Shio currents and the contact of subtropical waters with sub-Arctic.

The sub-Arctic water masses, in their origin and character, depend on the meteorological conditions on the mainland, and, of course, on the water masses which enter the region from the Bering and Okhotsk seas. They occupy the 300-m deep surface layer. In warm seasons only the upper 60-100 metres get warmed; while the layer below remains in a state of "liquid permafrost". This is called the cold intermediate layer. The 60-100 metres on top is the most active layer which influences the climate in the surrounding regions.

It was proved by investigations that the temperature of the active layer depends not so much on summer heating as on winter cooling and the relevant water convection. The cold intermediate layer rests on the warm intermediate

layer of Pacific waters and, further down, the deep and bottom waters.

Observations taken from the Soviet research vessel *Vityaz* have helped to fix the parameters of water masses in the neighbourhood of the Kurile-Kamchatka Trench where the stratification of water is in particular evidence (Table 9).

Table 9

Characteristics of water masses in the neighbourhood of the Kurile-Kamchatka Trench

Water layers	Depth in m	t°C	Salt content ‰
Surface, in spring and summer	0-100	2.6	33.2
Cold intermediate	100-250	0.3	33.3
Warm	250-850	3.5	34.1
Deep	850-3,000	1.7	34.7
Bottom	3,000-bottom	up to 1.01	up to 34.74

East of the southern and central Kurile islands, the temperature of the sub-Arctic waters is somewhat lower (1-3°) than south of the Komandorskiye and Blizhny islands (2-4°). The warm sub-Arctic waters penetrate into the northernmost regions because they mix with the waters of the warm Alaska Current which moves from east to west and replenishes the gulfs in the southeast of Kamchatka, creating favourable conditions for heat-loving fish.

Further south, the waters are cooled by the drainage of the cold waters from the Okhotsk Sea.

Having passed the Kamchatka Strait, the Kamchatka Current, under the name of Kurile Current (Oya Shio), descends to lower latitudes and reaches the Japanese islands. There it meets the subtropical waters of the warm Kuro Shio. Being colder and denser, the Kurile Current dives under the Kuro Shio and wedges in between it and the Japanese islands. Fig. 24 gives a good idea of how the two currents meet.

The further south, the deeper the Oya Shio sinks under the Kuro Shio. Beyond 35°N the Oya Shio's waters dissipate into the intermediate layer of low salt content, the so-called layer D which lies between the 300- and 1,000-metre levels,

But the two currents' front of contact is not stable. It easily changes its position. In 1951, for instance, the contact east of the 155°W was so faint that researchers christened it "a ghost contact".

We must once again point out that the sub-Arctic waters' course to the meeting place with the subtropical waters is unsteady and quite complicated. The waters may suddenly change their nature. In the northern regions of the Kurile-Kamchatka Trench and south of the Komandorskiye Islands and the Blizhny Strait, the sub-Arctic waters are slightly warmer than they are 1,000 kilometres and further south, because the northern regions are invaded by a warm current. The warm blend of Pacific and Bering Sea waters moves southwards into the zone of the sub-Arctic convergence. On the way it is cooled and saddled by the cold surface waters from the Sea of Okhotsk. The extent of cooling varies in different years. In warm seasons, the temperature of the Oya Shio waters, when they approach the sub-Arctic convergence, may drop abnormally. There are many reasons for this. First, their temperature depends on the severity of the preceding winter in the Okhotsk and Bering seas. That severity, in turn, depends on the winter temperature in the Asian mainland and the Arctic Basin which results from the temperature fluctuations in the surface waters of the North Atlantic and the European Basin.

So, the Oya Shio is cooled not so much by the waters of the northernmost Bering Sea as by the overlying waters of the North Okhotsk Current passing lower south. So the effluent waters will not become a dangerous source of cold, because on entering the Bering Sea and mixing with its waters, they, too, will be covered by the lighter waters of the North Okhotsk Current.

Moreover, the effluent waters will not spend all their cold on cooling the Kuro Shio. Along the 3,000-km route from the Bering Strait to the area of sub-Arctic convergence, some cold will be absorbed by the waters moving eastwards.

The assumption that the effluent waters would cool the waters in the Pacific's northwest negligibly and for only a short period of time is substantiated by two simple calculations.

1. Let us assume that all the 140,000 cu km of Arctic waters, having the extreme temperature of —1.7°C, have

been brought to the area of sub-Arctic convergence without any heat gains. Let us also assume that not a single cubic kilometre of the effluent waters dived down under the Kuro Shio and that on the way to Cape Shiono misaki the effluent waters had thoroughly mixed with the waters of the Kuro Shio (for its volume and temperature see Table 9). In such a hypothetical case the Kuro Shio's temperature will only fall by

$$16.5^\circ - \frac{16.5 \times 37.9 \times 10^6 \times 31.5 \times 10^6 - 1.7 \times 140 \times 10^{12}}{37.9 \times 10^6 \times 31.5 \times 10^6 + 140 \times 10^{12}} = 1.9^\circ$$

Let us recall that the annual amplitude of temperature of Kuro Shio's surface waters off Cape Shiono misaki comes up to 10° and higher (according to V. V. Leontyeva), and up to 13° (according to Y. M. Shokalsky). The fluctuations between the years near Taiwan are 3°, and in the south-eastern part of the East China Sea, 2.5°. Hence, the drop of 1.9° in extremely unfavourable conditions would not exceed the usual annual fluctuations.

2. It would take the effluent waters roughly a year and a half to pass from the Bering Strait into the area of sub-Arctic convergence. That would be long enough to have the 2-3 million sq km of the Arctic Basin's pre-Atlantic sector cleared of ice. The replacement of the ice and snow cover by surface water would increase the absorption of solar radiation by 32 Cal/sq cm/year. Without ever taking the extra heat from sea advection into account, we find that the changing albedo would produce an increment of $32 \times 3 \times \times 10^6 \times 10^{10} = 960 \times 10^{15}$ Cal/year.

In the final count, all these calories would heat the atmosphere, just as the annual fluctuations of cold reserves in the Okhotsk and Bering seas, would deprive it of approximately 400×10^{15} Cal/year.

The warming in the pre-Atlantic would be 2.5 times greater than the cooling which could be produced by the effluent waters in the northwest of the Pacific Ocean. That gives us the right to assert that the warming in the west of Eurasia would compensate the cooling in the east of Eurasia.

This conclusion is borne out by the latest research. It was established that the synoptic processes over the North Atlantic during the warming suppress the Asian maximum

and even eliminate it. The destruction of the Asian maximum and the entry of the western cyclones into the Sea of Okhotsk in winter create an exceptionally great impact on the development of the synoptic processes over the northwestern part of the Pacific Ocean because they bring heat into the eastern regions of Asia.

All this goes to show that the artificial discharge of 140,000 cu km of water into the Bering Sea from the Arctic Basin would be unable to cool the northwest of the Pacific, the northern islands of Japan, and the Soviet Pacific coast to any significant extent and for any appreciable length of time. The maximum anomaly which the cooling could produce would not exceed the level of cooling in the past 30 or 40 years. There would be no sudden drop in temperature. And at the worst, the cooling would not last longer than two years. Any abnormal cold in the winter is absolutely out of the question.

To be on the safe side, however, we should plan for some preventive measures in agriculture during the first year of pumping: planting more cold-resistant crops than we normally plant on the Soviet Pacific coast and North Japan, and protecting the perennial crops from possible spring frosts.

FIRST STAGES OF CLIMATIC AMELIORATION

> The key to the thermal conditions of continents lies in the thermal conditions of seas.
>
> *V. V. Shuleikin*

An analysis of climatic changes in the Cenozoic era reveals that they depended mainly on the water and heat exchange between the Arctic Basin and the Atlantic Ocean. Today man has the scientific and technical potential to control it prudently and safely.

In the past 20,000 years the climate has undergone many a dramatic change. For instance, the last stage of the Würm glaciation, 18,000-20,000 years ago, was the coldest time in the Anthropogene and the Middle Holocene, only 4,000-6,000 years ago, was the warmest in the postglacial epoch. At that time the mean annual air temperature in Central Europe was only a little lower than during the climatic optima: one degree lower than during the Likhvino optimum and just half a degree below the Mikulino optimum. The frequency and similarity in the fluctuation amplitudes give us the right to base our prognosis on the conditions which prevailed in the preceding periods of the Anthropogene which, as we know, lasted for 500,000 years. The factors and pattern which have governed the formation of climate in the past 20,000 years surely existed long before that.

Since we know the parameters of the water and heat exchange between the Arctic Basin and the Atlantic Ocean which governed the climatic changes on the continents, we should, in future, be able to regulate the climate at will. But for certain practical reasons, we will not be entirely free to choose the desired amplitudes.

It is clear that we cannot go ahead too slowly with the projected changes, since the self-cooling and the expansion of the ice cover will increase the operational costs. But equally we cannot just precipitate the process for fear of damaging the ecology of organic, and primarily, plant life. Finally, swift and deep changes would inevitably involve difficulties in providing power for the pumping systems. So, it would be best to handle the amelioration of the climate in several stages with an eye to the biological factors and the power supply.

The initial stages will depend on the capacity of the pumping systems (140,000 cu km/year). Let us take a closer look at them.

According to the paleogeographic data, during the Middle Holocene climatic optimum, the temperature of the Arctic Basin's surface layer in the pre-Pacific sector was near the freezing point (—1.6° in the Bering Strait). This is the best temperature for destroying the drift ice, at the lowest possible cost in labour and money.

Once the drift ice is destroyed, there would be no need to pump as much as 140,000 cu km/year, because the solar radiation absorbed by surface waters in the light seasons would prevent the basin from freezing up. So the pumping could be reduced by 30 to 60 per cent, otherwise the degree of warming would overlap the Middle Holocene optimum and reach the level of the culmination of the Mikulino and Likhvino interglacial periods.

During the initial changes in the Arctic Basin (from the present state of glaciation to stable ice-free conditions as in the Middle Holocene optimum), it would probably be advisable to pause for two or three years as soon as a thermal level was achieved equivalent to that of the early Middle Ages (900-1,000 years ago) when the drift ice melted completely in summer and reappeared in small quantities in winter. The pause would give us time to assess the results and mark any deviations from the planned parameters.

The preliminary calculations indicate that the pumping of 140,000 cu km/year of water from the Atlantic into the Pacific would ensure the best climatic conditions (similar to the conditions during early Anthropogene). It appears expedient to reach the levels of the preceding optima in the Anthropogene in four stages (Table 10).

Table 10

Stages of climatic amelioration in the first cycle

Stage	Equivalent optimum in the Quaternary period	Absolute dating, thousands years	°C above modern annual mean in Central Europe
I	Minor climatic	0.9-1.0	1.0-1.5
II	Middle Holocene	4-6	2.0-2.5
III	Mikulino (Riss-Würm)	70-100	2.5-3.0
IV	Likhvino (Mindel-Riss)	190-330	3.0-3.5

It is very difficult to make an accurate prediction of the Earth's thermal pattern and of dispersal of the heat at each of the stages. But since we are only outlining the future changes approximately, we can do with a simplified scheme of calculations. Let us take January, the coldest month, at the second stage. This corresponds to the average Holocene optimum, which we know well enough. So we can make a reliable forecast of the eventual improvements in climate.

First, we must establish the latitudinal temperature changes of the surface layer of water from Florida Strait, through the European Basin and the North Pole, to the Bering Strait and onwards to Iturup Island. Then we must examine the changes in air temperature at sea level in the same section; finally, we must take the size of future anomalies at the key points of the route into account to make a comparison of present and future temperatures. These anomalies are the basis for the isanomal charts for the entire Northern Hemisphere, taking the following into account:

1. A number of researchers have found that when the warm currents, moving from the outlying seas (from the Barents to the Chukotka seas), increase in volume, Eurasia's isanomal lines turn their front of almost perfectly parallel rows to the common coastline. The increasing influx of heat compels the isanomal lines to move in a clockwise direction. They pass at an acute angle to the latitudinal lines, particularly in the Siberian plains where their trajectory is not distorted by mountain ranges.

2. The isanomal lines double round, within a hair-breadth of the coastlines because the heat from the warm water masses compensates for cold impact of the land.

3. All warm currents from the outlying seas merge into one and move as though they have a common origin whose temperature gradually falls on the way from the Atlantic to the Bering Strait.

4. The air masses brought to the ocean surface change readily enough. That is why the pattern of the air temperatures is so like the pattern of the ocean surface temperature.

5. The effects of the warm currents can penetrate deeply inland. For example, even nowadays, any rise in temperature in the Arctic and a change in the Gulf Stream warming immediately affect the climates in the Ukraine and Eastern Siberia.

6. The effects of heat brought to the mainland largely depend on the landscape. Mountain ranges halt its inland progress and reflect it. When the ranges reach an altitude of 300-400 metres, the turbulent heat conduction is reduced by 50 per cent, but when they are more than a kilometre high, it is reduced to one-seventh. The shielding effect of the mountain ranges varies with their length, especially where the heat waves can easily outflank them.

The isanomal chart* serves as the basis for the chart of isotherms. In Fig. 25 the new temperature pattern is superimposed on the old, for easy comparison. The new temperature pattern in the Northern Hemisphere corresponds to the last stage, when the drift ice is completely melted.

If, after a brief pause once the sea ice is melted, we resumed pumping at a rate of 140,000 cu km of water a year, the temperature of the World Ocean surface, as in the bottom layer of the troposphere, would begin to rise. This would mark the beginning of the third and eventually the fourth stages of the climatic amelioration.

So, in the first stage the climate would reach the level of the 9th and 10th centuries A. D. At that time the Arctic Basin's ice sheet melted in the summer, and reappeared to

* To avoid large marginal errors, the isanomal chart was checked on the basis of temperature gradients (established by Y. V. Osmolovskaya) and the law deduced by V. V. Shuleikin, under which the temperature anomaly decreased with the progress of warm air currents inland.

a small extent in winter. The seasonal change in glaciation would be reminiscent of the present régime in the Sea of Okhotsk where the ice melts completely in the summer and covers three-quarters of the surface in the winter.

In the first stage the winters would become milder, the vegetation period longer, with less frequent early autumn and late spring frosts. There will be fewer years of drought and the general improvement in the climate would stimulate many of man's activities, particularly agriculture.

The first stage would last not longer than two or three years, because the duration would depend on scientific and technological rather than on biological factors.

There would be much greater changes during the second stage. Their effects would repay effort expended and implement the subsequent stages generously. The change in the state of the surface water will result in a thermal leap: the ice-free water would absorb a good deal of the solar radiation which is now uselessly reflected into space by the snow and ice. In the Soviet Arctic the temperature would rise most in the coldest regions. The effects are presented in graphic forms in Fig. 25.

Since the surface layer of warm Atlantic waters would heat the surface waters in the Arctic Basin more or less evenly, the temperature along the whole Eurasian coastline would also be made more uniform. And it would rise higher than during the climatic optima earlier in the Anthropogene. In a word, the direct flow would not only bring heat, it would distribute it more evenly along the Eurasian and North American coast. Take, for instance, Eurasia's Arctic seaboard. Today the January temperature fluctuates at various points by as much as 30° (0° at Lofoten Islands, —30° in the neighbourhood of Wrangel Island and Novosibirsk Islands, —20°C at Diomede Islands). The new thermal régime would reduce these differences to a mere 8-10°, while raising the overall temperature: e.g. 8° at Lofoten Islands, and 0° on islands in the East Siberian and Chukotka seas.

Once the drift ice is gone, the Arctic Basin would be open for all-the-year-round navigation. The seas in the Far East and the river estuaries in the Arctic sector adjacent to the Atlantic would also be opened to year-round navigation.

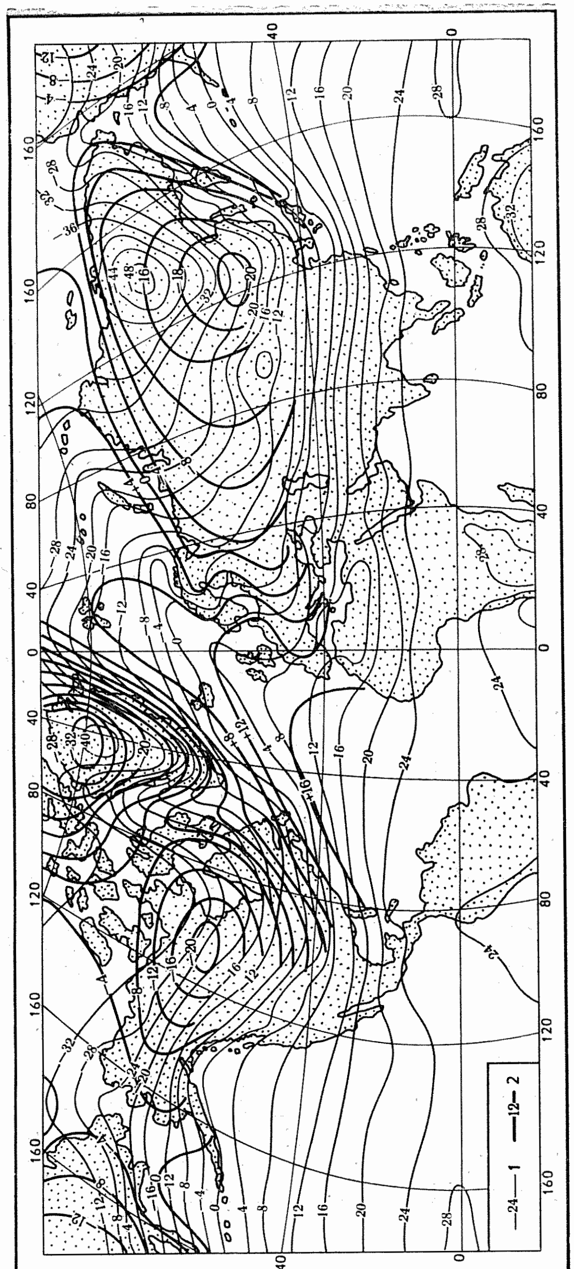


Fig. 25. Map of January isotherms of air at sea level (T°C)
1—present isotherms;
2—isotherms in the second stage of amelioration

The northwest of the European part of the Soviet Union will have winters that would be like present-day winters in Denmark and Southern Norway and the climate in the North Urals and Taimyr very much like Central Sweden. In Moscow Region the winters would be as warm as in the West Ukraine.

In the West Siberian plains, the January temperature would rise by 10° or 20°, with a greatest rise nearer the Arctic Basin. As the melting of the Arctic ice would do a great deal towards neutralising the avalanches of Arctic air, the new thermal régime would be conducive to growing the same crops as in the northeast of the Ukraine. Winters in the North Siberian plains would resemble the middle and lower reaches of the Volga; in the East Siberian lowlands the coldest and most continental regions in the USSR, the temperatures will be comparable to the West Urals today, but there, too, the climate would acquire typical oceanic features.

The lands covered by the Arctic and sparsely forested tundra (nearly 35 per cent of the Soviet Union's territory) would become biologically and agriculturally more productive, and could be used for extensive cattle-breeding.

The permafrost, which covers 47 per cent of the Soviet Union, would disappear in the upper layers and the territory would become accessible to normal industrial and agricultural development.

Winter frosts generated by the avalanches of Arctic air masses and the Asian maxima would recede in duration and vigour, and would no longer inflict economic losses.

The damaging late spring and early autumn frosts would weaken and eventually disappear. Frost-free periods would lengthen all over the Soviet Union, even in the mountain regions.

Winters in cold cities like Perm, Sverdlovsk, Omsk, Novosibirsk and Irkutsk, where the mean temperature drops to —16°, —19°C in January, would be milder, more like the winters in Kharkov, Voronezh, Volgograd, Saratov and Kuibyshev, respectively.

Yakutsk and Verkhoyansk lie within the range of the pole of cold. Winter temperatures there drop to —50° or even —60°C. The planned warming would bring the temperature in the neighbourhood of Verkhoyansk to the level in

Lvov and Kiev; Yakutsk would have winter temperatures similar to Kursk and Astrakhan. The pole of cold, now in Oimyakon, would be less severe and, in winter, it would move to the border junction of the USSR, the Mongolian People's Republic and China, and its mean temperature would rise in January from —48° to —20° in the second stage of the climatic amelioration. In Oimyakon itself, the mean January temperature would rise by 30° (to —16° or —18°). Greenland would be the coldest place in the Northern Hemisphere but, deep inland, its mean January temperature would rise from the present —40° to —32°C.

Continental climatic features would recede everywhere, and, in the USSR, particularly in Siberia where they are most prominent. The changes for the better would be mainly brought about by the absence of the Asian anticyclone. Winters in Eastern Europe, Central Asia and Siberia would no longer be so rigorous; the winter monsoon would subside; the coastal waters in the Far Eastern seas and the Pacific northwest would become much warmer.

The navigable period on all rivers in the USSR would be longer. The Volga and its man-made seas would be navigable throughout the year. The rivers west of the Volga would also be open to shipping all the year round.

The borders of the organic world in the Soviet Union will advance northwards; vast regions will be opened up to flourishing organic life; the duration of the vegetative period will be extended; in the south it would be warm enough to bring in two harvests a year.

The Arctic Basin could become one of the World Ocean's most productive regions. Fisheries would thrive along the coast of the Northern seas because the belt of continental shoals in the littoral zone there is particularly suitable for marine life.

The mineral resources on the northern fringes of the continent, which are now inaccessible because of cold summers and long and rigorous winters, could be developed.

The Atlantic and Arctic oceans would give up some of their water to the overhead air masses, which would bring a higher rainfall to droughty regions, deserts and semi-deserts in the USSR; the rivers would rise so that the hydroelectric power stations would produce more power with only nominal outlays. The increase in the output of electric

power should suffice to operate the interoceanic pumping stations.

The climate outside of the USSR—in Western Europe, Mongolia, Northern China and Japan—would also improve. The recession of the Canadian anticyclone, which prevails in North America, would ameliorate the climate over the greater part of that continent. The permafrost, which extends to the southernmost tips of Hudson Bay, would disappear in the upper level except for a narrow strip surrounding the Greenland glacier. Higher winter temperatures would reduce the climatic contrasts between the northeastern plains (long winters, low temperature, short and cold summers, insufficient precipitation) and the southern prairie belt; the continental climate would wane; the vegetative period would be longer; heat- and moisture-loving plants, including farm crops, would thrive on the former cold-bound plains.

Many researchers dreamt of neutralising the impact of the cold Baffin Bay, Labrador, Cabot and other currents on the eastern coast of North America. The Bering Strait Dam project would take care of that and bring the long-sought-for heat to the eastern coast of North America. The Gulf of Saint Lawrence would at last be open to navigation all the year round; ships, often unaccompanied by ice-breakers, could pass through the straits in the Arctic Archipelago at all seasons.

The extreme aridity of the Sahara and other deserts would decrease and they would become more habitable. This is also true of the deserts in Soviet Central Asia. There is an erroneous opinion that these deserts are responsible for aridity in the south of Russia. Refuting the opinion, the Soviet climatologist A. A. Kaminsky said: "It is not the dry air from Central Asian parched deserts that is responsible for the droughts in the steppes of Kazakhstan and the European sector of the Soviet Union, but, on the contrary, the desert itself owes its existence to the impact from the north."

The air and water jackets of the Earth are, so to speak, an integral whole; they are held together by friction, heat and moisture exchange. That is why the warming of the Northern Hemisphere in its upper latitudes would be accompanied by a similar warming in the polar latitudes of the Southern Hemisphere. The sea routes along the Antarctic

coasts would become more accessible, which would facilitate communications. The continental anticyclone over the Antarctic would decline in force and lose some of its stability. The waves of air masses from the surrounding oceans would penetrate deeper into the Antarctic's central regions, and the anticyclone would no longer beat them back. There would be higher rainfall, and the ice balance of the Antarctic shield would also be improved.

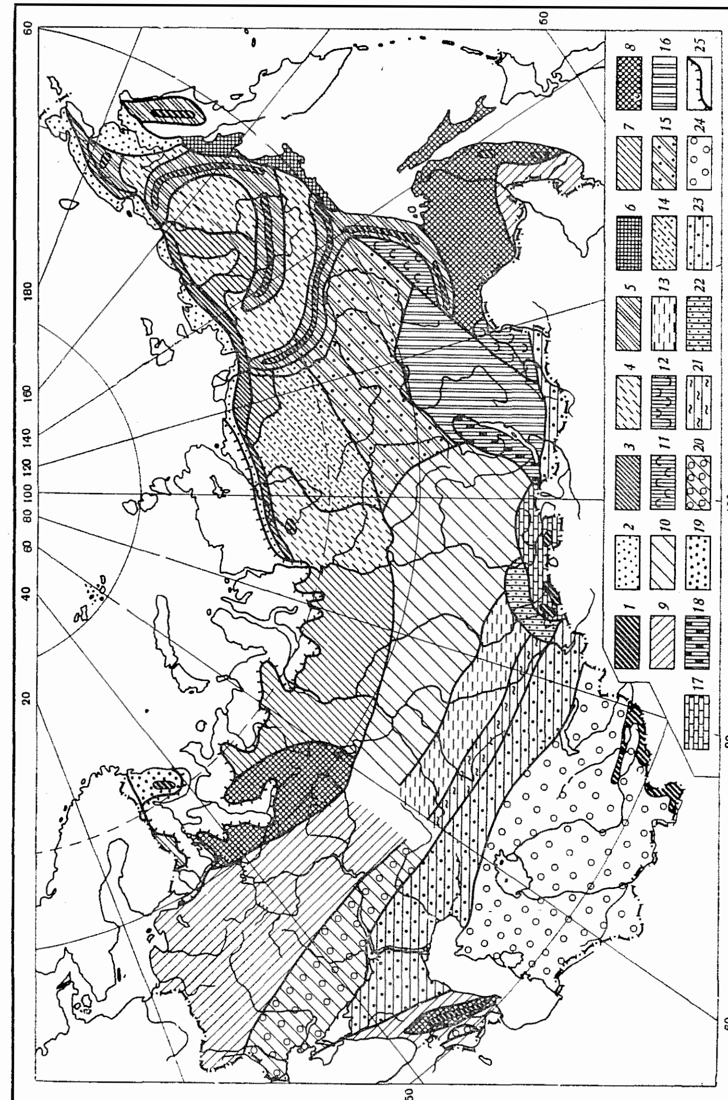
The general atmospheric circulation would be conducive to the amelioration of world climate, and it would affect the whole planet. This can be substantiated by paleogeographic data and plant fossils found in the geological strata all over the world.

But enough of speculation. Let us look for tangible proofs in today's observations of nature, in which time is preserved as in a magic mirror. To avoid comparisons involving gigantic periods of dozens of millennia, let us simply compare the usual seasonal fluctuations which can be observed every year. The temperature contrast between the North Pole and equator in January, for instance, is anything up to 56°, but in July, it is only 28°. This is because in summer the temperature at the pole rises to 0°C, while the level at the equator, remains unchanged, at 27-28° throughout the year.

And so, in summer when the temperature contrast falls to 28°, and the atmosphere is least disturbed, there is more rainfall, and the continental climatic features soften.

The direct flow would force the present summer régime

Fig. 26. Schematic diagram of vegetation in the USSR in the Mikulino interglacial epoch (T. D. Boyarskaya, 1965)
1—alpine tundra and plants; 2—plain tundra; 3—forest-tundra; 4—deciduous and mixed forests (on plains and plateaus); 5—deciduous and mixed (alpine); 6—dark and light conifers; 7—dark conifers; 8—conifers and broad-leaved; 9—broad-leaved; 10—pines and cedars with some firs and broad-leaved species; 11—deciduous and birch with some dark conifers and broad-leaved species; 12—mixed conifers with a few broad-leaved species; 13—narrow-leaved with some broad-leaved species; 14—deciduous and mixed steppe species; 15—conifers with patches of narrow-leaved steppe species; 16—light conifers, narrow-leaved and steppe; 17—cedar, fir and steppe; 18—cedar, pines and birches; 19—firs, pines and birches; 20—broad-leaved; 21—narrow-leaved; 22—dark conifers; 23—steppe; 24—desert; 25—margin of sea transgression



on the Arctic Basin's centre in January. Therefore, we have every reason to expect the beneficial changes, which now only take place in summer, would affect the atmospheric circulation and its heat and moisture exchange with the World Ocean. But the changes would last much longer, taking in a part of spring and autumn.

Weather and climatic fluctuations under the new heat conditions are also possible. However, they will be smaller and less frequent. And if the long-term forecasts became sufficiently accurate, we should be able to prevent them. The direct flow system is so elastic that it could regulate the surface temperature of the North Atlantic, and the European and Arctic basins. By receiving timely warnings of undesirable heat waves or cold snaps, we would be able to control the direct flow and prevent any dangerous deviations from the normal before they got the chance to develop.

In a word, the controlled and well-regulated direct flow would be a best regulator in the northern (the coldest) region of the World Ocean, which could be used as a climatic regulator on a global scale.

Before passing from the second to the third stage of climatic amelioration, we shall have to determine the reaction of fauna and flora to the changes in their ecological conditions as accurately as possible. It is hard to predict the speed at which the vegetation would be moving its boundaries. The botanists would undoubtedly find ways to help the forests to take over the newly available expanses and to speed up their advance towards the shores of the polar seas. During the current Arctic warming they have advanced at an average of a kilometre a year. Once the drift ice is melted, moderate pumping should not last too long. After the second stage and a pause of a few years, the volume of pumping should again be increased. This would usher in a new phase of climatic amelioration, with the level of the Mikulino interaglacial period as a goal.

In Central Europe, the mean annual temperature would gain approximately 0.5° over the second stage. Although the isotherms would keep the same basic configuration (Fig. 25), the areas of the negative isotherms would contract slightly as the areas of the positive isotherms expanded. The changes in the isothermic boundaries would be followed by changes in the boundaries of vegetation.

Fig. 26 shows a map of vegetation in the USSR during the Mikulino interglacial period. It may be taken for practical purposes, as a map of vegetation for the third stage of climatic amelioration, since the third stage would, as we said, be similar to the Mikulino period in the Anthropogene.

The tundra and forest-tundra zones would be confined to a very narrow strip, and would probably disappear altogether in the west, remaining only on, and to the east of, the shores of the East Siberian Sea. The polar regions of the USSR European part would be covered by coniferous forests. The broad-leaved forests would advance northwards. The Atlantic species, including the beech and hornbeam, would spread from the west as far as Moscow meridian. Broad-leaved trees, intermingling with coniferous trees, would cover the entire area to the east of the Urals. The advancing forest-steppes would cut into the northern boundaries of the Central Asian deserts.

In the USSR, and on all the continents, the number of heat- and moisture-loving plant species would increase over the second stage.

In the fourth stage, which would be the equivalent of the Likhvino interglacial period, the warming would continue. The mean annual temperature in Central Europe would rise by another 0.5°. Fig. 25 shows that the additional warming will further contract the areas of the negative isotherms, while expanding the areas of the positive isotherms. The isotherms —20° and —18° would disappear in North America and Asia; the isotherms —32° and —30° on Greenland glacial shield would probably also vanish; but the January 8-9° isotherm which passes along the centre of the Spitsbergen Current, would double Spitsbergen and Franz Josef Land, and the zero isotherms in the Arctic Basin and the Bering Sea would be dissipated by the above-zero temperatures.

The basic temperature pattern would be more or less the same as in the second and third stages. The vegetation zone would move nearer the pole.

PRACTICAL IMPLEMENTATION PROBLEMS

They say that the Arctic ice hummocks are invincible: nothing of the kind! We can conquer the ice hummocks, but not human superstition.

S. O. Makarov

A glance at a map of the Northern Hemisphere is enough to see the advantages of the geographical position of the Bering Strait for the transfer of water between the Atlantic and Pacific oceans via the Arctic Ocean which spreads lengthwise along the zero meridian. It is not surprising that as early as last century man turned his eyes to the Bering Strait in the attempt to find the key to controlling climatic modifications. The Arctic with its mammoth stocks of stagnant ice gave ample food for thought. It seemed that nature herself was pointing to this canal for conducting heat into the Polar basin to melt its ice cover.

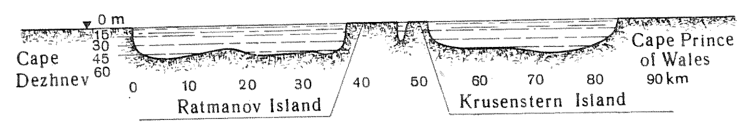
The Bering Strait is 85.2 km wide (Fig. 27). In the narrowest place, at the Diomede Islands (74 km), it is quite shallow. The maximum depth is 59 metres, the average, only 50, so the area of the clear opening is 3.76 sq km. To pass the planned 140,000 cu km/year of water through this bottleneck, the effluent waters would develop an average speed of 1.2 m per second.

During the construction of the dam and in the first years of pumping the strait would be packed with drift ice. This is very important, and so let us study it more closely.

According to the sailing directions, navigation in the Chukotka Sea opens some time between June 25 and July 18, and closes between November 11 and December 15. The earliest complete freeze-up of the sea was registered on September 6, the latest, on February 6. Late in September, the sea begins to freeze in the south. The northerlies blow in October and November, driving in the ice from the heart

of the Arctic Basin through the gap between Wrangel Island and Alaska. The ice fills the entire sea and obstructs the passage to the Bering Strait. In winter the ice moves very slowly, but never comes to a complete standstill.

In November and December the winds pack hummocks of new ice. The floes and tracts of ice move at different speeds, piling up on the way or making room for short-lived sheet water and ice-free lakes. In February or thereabouts, the process begins to involve perennial ice. The chaotic motion presses the ice into a compact mass. However, the winds are so strong that they drive the compact ice masses over great



Horizontal scale 1 mm = 1 km
Vertical scale 1 mm = 5 m

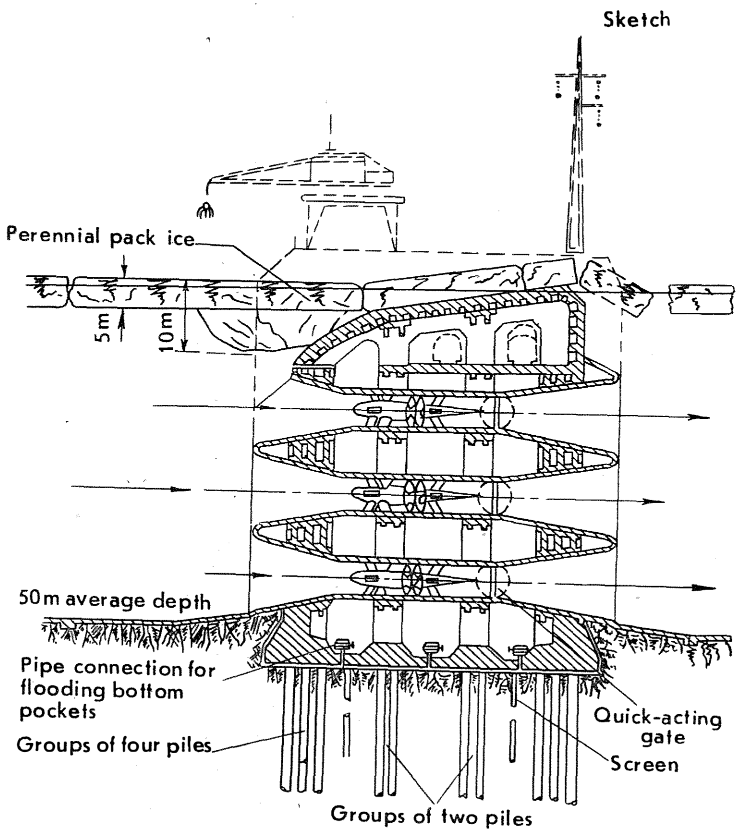
F i g. 27. Profile of the sea bottom in the Bering Strait

distances and force them to pile up ashore. Air reconnaissance indicates that the entire surface from the Bering Strait to Cape Schmidt is frequently packed with heavy hummocks.

But the winds from the mainland, if they blow long enough, drive the ice offshore, making big ice-free lakes. The surface from the Bering Strait to Cape Serdtse Kamen (about 130 km in radius, as seen from a plane) has several times been completely free of ice. But usually the fast ice is strong enough, and its thickness is not less than 145-175 cm.

The hummocks are thrown together by sea currents, tides and, above all, winds. The stronger the wind, the more ice hummocks it piles up. V. Y. Vize claimed that restless atmospheric conditions, i.e., when fresh and strong winds frequently change their direction, are probably most conducive to the formation of ice hummocks. The wind's role in destroying the fast ice, which obstructs early navigation, is just as important.

Most of the underwater hummocks and ice stacks come to the Chukotka Sea from the East Siberian Sea, that is, from the north and northeast. In the horizontal plane these ice-floes only have an area of a few square metres, but vertical-



F i g. 28. Cross-section of the dam

ly, they are 3-11 metres, sometimes, 20 metres thick, less than 13 metres of which are under water.

They are driven in by winds, rather than by tides (which are quite low in the Chukotka Sea). The Arctic slow currents are not capable of piling up such great hummocks as these either.

These are the icefloes which would run up to the Bering Strait bottleneck.

Would they jam the strait and prevent the pumping of waters from the Chukotka Sea into the Bering Sea? No, our calculations rule out such a threat.

The sea depth in the neighbourhood of the proposed dam

will range from 55 to 60 metres. But, as we know, the underwater portion of this perennial pack ice is usually less than 13 metres. The surface area is also small. Therefore, the ice would not take up more than 5-10 per cent of the cross-sectional area of the dam.

However, stormy weather (50 days a year, on the average) can drive the ice fields over great distances from north to south. On encountering the dam's rigid body, the ice would pile up in front of it in the same manner as it does on the coasts. That is why the dam's upper deck would need to be streamlined (Fig. 28).

In that case, if the pressing ice ran into the dam, its streamlined top would minimise the horizontal force. So the ice will waste its energy on climbing the dam and toppling over at the other side. The streamlined shape would facilitate the climb and fall of perennial pack ice up to 5 metres thick, and icefloes, 10-12 metres thick. If need be, the dam's shape could be altered during the construction so as to afford passage for larger icefloes.

We could help the ice to make its way over the dam by reducing friction to a reasonable level. But even if we did not do this, the friction would still be less than in the case of the *Fram* whose sides and bottom withstood the onslaught of icefloes in the heart of the Arctic Basin brilliantly although the formation of hummocks is much more vigorous there than anywhere else.

We must not forget another important circumstance. The ice moves more easily in the Chukotka Sea than, say, in the Spitsbergen-Greenland Strait. First of all, the Bering Strait is 1,500 kilometres further south, and so the sea absorbs more solar radiation. Secondly, the bottom of the drift ice would be constantly washed by the running waters with a temperature a few decimal points above freezing. The experience accumulated by the hydro-electric power stations in the north shows that the moving waters reduce the thickness and strength of ice long before it reaches the dams. Observations of the state of ice at the Angara's exit from Lake Baikal reveal that the exit point does not freeze at all. And the winter temperature in the Bering Strait is not lower than at the Angara's exit, while the salt content is higher, so that the formation of ice would be delayed, and its strength diminished.

The streamlined top is not the only means of preventing or weakening the accumulation of ice north of the dam. There are some other possible methods:

—transfer of the dam's axis behind the Diomede Islands or even into the straits of Chirikov and Spanberg (in the range of Saint Lawrence Island) where the temperature is higher than in the Bering Strait; in that case the speed of the ice can be reduced by a third. Moreover, the winds there are not so restless, and so the ice pressure would be weaker;

—erection of an ice barrage north of the dam;

—blackening of the ice surface in the light period, and year-round air bubbling with the view to weakening the ice and reducing its thickness;

— employment of powerful ice-breakers and explosives for crushing ice, using helicopters and submarines for the purpose;

—installing special pumps which let finely crushed ice through;

—installing reversible pumps at the top of the dam to push the ice back when it piles up too dangerously on the northern side of the dam. The backthrust should work at the rate of 4 cu km per hour which is the equivalent of the present volume of the south-to-north drift.

And what about the dam itself? What will it be like?

First of all, it will have to comply with the geographic, hydrological, climatic and seismic conditions in the Bering Strait. We must also realise that the dam will be erected far from industrial centres and habitable regions. There are no railways in those parts, and the navigation period is very short. But the construction will call for the delivery of tremendous volumes of heavy freight. So it should be designed for large-scale on-the-spot assembly out of big blocks brought in afloat by sea.

The latest successes in the production of ferro-concrete and high-grade hydrotechnical cements, as well as the higher precision in the calculations of thin-walled structures, make it possible to take the preliminary decision of building the dam from separate three-dimensional sections in the shape of pontoon units. Cold-resistant ferro-concrete should be employed as the principal building material; the inside

parts (gates, partitions, platforms, stairways, and so on) should mostly be made of aluminium alloys.

The width of pontoon units should correspond to the width of the dam minus its fairings, but not less than 40 metres; the length, not less than 250 metres, may vary according to the requirements of sea transportation; the height, from 20 to 60 metres, will vary with the depth of the particular section.

The blocks should be construed as honeycomb boxes, the number of vertical cells varying from one to three, depending on the height of the section; on the horizontal plane, the length of the section would determine the number of cells, but at all events there should be at least twenty. Because of the box-type configuration with interior infusers and diffusers, the barriers in front of the structural elements would ward off excessive pressure. The durability of girders in the meridional plane could be ensured without unduly cramming the dam's interior. When the ice pressed against it from both sides, the stability could be ensured by a ramified system of anchors.

The designs of the pontoon units should envisage their possible utilisation as berths or as warehouses and workshops during the construction period.

Once the drift ice was destroyed, the streamlined top would be altered to make room for a double-track, standard-gauge railway and a two-lane road.

The dam should be prefabricated at major building bases, leaving only the actual assembly of the sections to be done on site.

The sections should be made at shipyards or similar enterprises in warm climatic zones, close to industrial centres. They will probably be located in Vladivostok, on the west coast of the USA and Canada, and in Japan.

The blocks could then be hauled to the Bering Strait by sea and the bottom of the strait should have been prepared by then. The anchorage, depending on the geological structure of the bottom, would be effected either by piling or drilling.

The strength and stability of the blocks and reinforced anchorage would help the dam to withstand the horizontal pressure from waves, ice and currents without any further expensive structures. Such dams can be built easier and faster than conventional solid-body dams.

From the sailing directions dealing with the hydrometeorological and hydrological conditions there we must assume that it would take five or six months to haul the blocks over to the Bering Strait with the help of an ice-breaker. The shores there are very jagged. The depths would allow us to pile up the blocks close to the axis of the dam. Since modern vessels pass the winters in fast ice, particularly in bays and gulfs, tolerably well, the winter storage of blocks would present no danger. Consequently, the freezing of the Bering Strait and the north of the Bering Sea will not shorten the time for the building work. At least six months in the year are available for block installation and exterior work, and 8-10 months, for anchorage. Interior work will not be seasonal.

The tides in the Bering Sea and its neighbourhood are low, so they will not present any difficulties either to building or operating the dam.

Special rotary-blade, axial direct-flow pump units would be installed in the dam. The electric motor, reduction gear and the pump in these units are in one closed streamlined unit. The turning angle of the pump blades would be set by an automatic unit which would keep track of the water level on both sides of the dam and respond to the changes wrought by the winds and tides.

Emergency gates would shut off the water flow through the dam when the pumping units stop working.

Given the goodwill of the countries involved the whole complex of hydrotechnical structures would be completed in eight or ten years.

It is not so easy to arrive at the electric power requirements because of certain difficulties involved in the calculating the difference of levels on both sides of the dam. That is why we shall give only approximate figures for the principal components: water speed at the inlet of the pumps—5 cm per second; lost pressure at entry (to overcome the resistance the flow encounters in the Chukotka Sea shelf)—10 cm per second; static back pressure (exerted by the Pacific waters on the southern side of the dam)—10 cm per second; lost pressure at discharge (to overcome the resistance encountered by the flow in the Bering Sea shelf)—5 cm per second; other losses—5 cm per second. Total—35 cm per second.

Since there is no accurate data, we cannot include wind direction and force in our calculations. The only reliable information we have is that the dominating winds in the Chukotka Sea are from the north, i.e., the general wind direction is favourable to the north-to-south water discharge.

Given the summary pressure of 0.35 m per second, the power needed to drive the pumps will amount to

$$W = \frac{140 \times 10^3 \times 10^9 \times 10^3 \times 0.35}{31.5 \times 10^6 \times 102 \times 0.7} = 22 \text{ million kw},$$

where $140 \times 10^3 \times 10^9 \times 10^3$ stands for the annual pumping volume in kg; 31.5×10^6, for the number of seconds in a year; 102 kg m/sec, the equivalent of 1 kw; and 0.7, the efficiency of the pumping systems.

Let us add 5 per cent of the sum for auxiliary work, and 4 per cent for losses in the electrical network and for power transformation inside the dam. Then the overall capacity will amount to approximately $22 \times 1.05 \times 1.04 = 25$ million kw. Compare that with the capacity of the Bratsk hydropower station (4 million kw), the Krasnoyarsk hydropower station (6 million kw), and the projected Lower Lena hydropower station (20 million kw).

Where is the electric power to come from? By 1980 there will be many economical atomic power stations. But that is not all. Hydropower resources are abundant in British Columbia and the Chukotka Peninsula. Lately, major gas and oil deposits have been discovered in Alaska; they are estimated at thousands of millions of tons. Gas and oil have been found in Northern Canada, and in the USSR in the estuary of the Vilyui, and in the vicinity of the Verkhoyansk flexure. We can expect to find large and economic deposits there, too, as well as in the neighbourhood of the Chukotka Peninsula.

Finally, electric power stations could be built directly in the Lena, Zyryanka and other recently discovered coalfields. The deposits there can be worked on the open-cast system. The power stations would be economic since they would be equipped with 1-1.5 million-kilowatt units.

Designers are working on major power transmission lines, covering several thousand kilometres. The lines will cross major production centres of coal, oil, gas and electric power. Several transmission lines, from 2,000 to 3,000 km

long, are presently being designed in the USSR to transmit electric power from the Yenisei projects to the Urals. Such lines, built two or three side by side, can transmit up to 10 million kw. The Institute of Direct Current asserts that it is practical to transmit power from Krasnoyarsk to Moscow over a distance of 4,500 kilometres. It is advisable to transmit the electricity over several lines with an annual capacity of 25,000 million kwh each.

In a word, we already command the technical means to feed the pumping systems in the Bering Strait with power from a variety of sources. After the decision to build electric stations and high-tension lines is taken, the requirements for electric power could be fully met in seven or eight years.

What would this unique hydro-engineering complex in the Bering Strait cost? What capital investments will have to be made?

We must note that in planning the outlays for even such familiar projects as big hydroelectric power stations, estimates can sometimes err by as much as 25 per cent in either direction. So imagine what it means to calculate the cost of the Bering Dam project, to be built in exceptionally severe climatic conditions, far away from centres of population and industry.

But we must establish, even if only approximately, the capital investments required for the whole complex of hydrotechnical, industrial, transport and civil structures.

For that purpose we made use of data in special literature dealing with the cost of similar projects, including the cost of equipment, prefabricated sections, assembly, and so on. We based our calculations on the principle of maximum cost, that is, when in doubt, we took the highest figures.

In this way we estimated that the overall cost would amount to roughly 24,000 million rubles. The sum will cover the labour cost, and the cost, including transportation and assembly, of the blocks, equipment, steel sections, pumping machines, fairings, passageways for fish, and sluice chambers for shipping; the cost of building dams for the railway and highway, new towns on both sides of the strait, each for 50,000 inhabitants, two sea ports and two airports, electric power plants with all subsidiary equipment including urban settlements; fuel enterprises for the power stations and auxiliary services, roads, industrial enterprises,

settlements, power transmission lines, auxiliary industrial enterprises (special shipyards, roads, ports, berths, warehouses, building machines, loading machines, and so on); and cost of research, surveying and designing.

But when the dam is completed, part of this outlay would be recovered from the sale of building machines, equipment, transport facilities, temporary structures, etc. no longer required. This normally works out at around 8 per cent of the overall investments. So the actual capital investments would total 22,000 million rubles.

The investments would work out something like this: the hydroengineering complex in the Bering Strait—13,700 million rubles; fuel enterprises—1,800 million rubles; power stations—3,500 million rubles; high-tension lines—3,000 million rubles.

The structures relevant to the production and transmission of electric power should cost around 8,000 million rubles. But we must not forget that once the ice is destroyed, the consumption of electricity would drop to about half and the extra power capacities would then be available for other purposes. So in effect this would further reduce the real overall cost from 22,000 to 18,000 million rubles.

These estimates are in no way understated. Here is an example for comparison. The capital investments in the Krasnoyarsk hydropower station, one of the largest in the world, worked out at 168 rubles per kilowatt capacity. In the Bering Strait Dam we have allowed for 550 rubles per kilowatt, i.e. approximately 3 times as much. But the investment for the construction of the Cheboksary, Saratov and Lower Kama power stations was 560 rubles per kilowatt, slightly more than needed by the Bering Dam project.

The Soviet Union would not be the only country to profit by the project. Since climatic conditions would change for the better all over the world, the execution of the project will involve many countries, and they would have to set up an international agency. Contributions to the capital investment fund, building, delivery of equipment, structures and materials, transportation, power supply and maintenance would have to be related to the economic advantage each country was likely to gain.

The USSR's share in the investment fund would probably not exceed 40 per cent, plus 10-12 million kw of electric

power. This outlay is quite reasonable. According to the latest data, the USSR commissions power stations to the tune of 12 million kw a year. The investments in the project would constitute less than 1 per cent of the planned investments in the national economy in the next ten years, and 0.3 per cent of the investments in the following decade.

The North-American power scheme we mentioned previously would require investment of a total of 100,000 million dollars, i.e., four times more than required by the Bering Dam project.

The decontamination of lakes and rivers in the United States and the prevention of their further pollution would cost about 40,000 million dollars, not to mention the cost of the industrial enterprises for the treatment of sewage. That is much more than it would take to build the whole dam.

It all goes to say that the appropriations for improving the global climate are reasonable. Moreover, they would be recovered quickly.

FURTHER PROSPECTS OF CLIMATIC AMELIORATION

Climatic changes depend on the redistribution of strong oceanic currents.

L. B. Rukhin

All the hydrodynamic, thermic, technical and economic calculations presented above were made to prove that the ice in the Arctic Basin can be destroyed. However, the very same calculations corroborate, in passing, that given equal capacities of electric power stations and pumping systems plus the subsequent rise in the radiation balance, we may expect much better results, i.e., we can achieve a climatic optimum like the Likhvino (Riss-Mindel) period (Table 10). The potential inherent in the Atlantic-to-Pacific water transfer can help us even beyond the original task of climatic amelioration.

The atmosphere itself does not generate heat, it simply picks up heat from the sea surface. But the ocean gives up its heat reluctantly, wasting no more than 10 or 15 per cent of its thermal balance on the heat exchange with the atmosphere. Moreover, it gives up the heat very evenly over vast expanses. The South Atlantic, the Pacific and Indian oceans give the atmosphere equal amounts of heat—10 Cal/sq cm/year. A considerable area in the Central Pacific releases no heat at all. The heat is only released on any scale in the areas of contact between warm and cold waters (the Gulf Stream and Labrador currents, the Kuro Shio and Oya Shio). Naturally, when the Arctic diminishes its remission of cold, the contact areas will also decrease their heat expenditure.

In practice, the underlying layers are little influenced by heat. Y. M. Shokalsky noted that "if the layer of surface water were heated continually and evenly for a span of a hun-

dred years until its temperature reached 30°, the water temperature at the depth of 100 metres would suffer no changes. But after a thousand years, the water at 100 metres would have a temperature of 7.3°, and 0.6° at 200 metres. It would take 10,000 years to raise the temperature by 0.01° at the depth of 1,000 metres."

The underlying surface expends its heat in long-wave radiation. The expenditure is proportionate to the fourth power of the absolute temperature of the underlying water. But the higher the temperature of the water, the greater the atmospheric humidity. When the humidity rises, the atmosphere begins to curb the long-wave radiation from the ocean surface waters. That was why in the past we always had excellent climates during periods of normal solar activity. The conclusion is that when the volume of the surface waters reaching the Pacific from the Atlantic Ocean exceeded 140,000 cu km/year, the temperature differential between the equator and the North Pole would be greatly reduced. The gap between their thermal régimes would be bridged because of the rise in the temperature of the Arctic surface waters and the reduction in radiation of heat into interplanetary space, and not because of the temperature drop at the equator.

To visualise the effect of the interoceanic water exchange in the distant future, we must again refer to the climates of the past. It was established that the cooling and warming in late Pliocene (0.5-2 million years ago) were different from those in the glacial and interglacial epochs of the Quaternary period (20,000-500,000 years ago). The former were milder than the climatic changes provoked by the transition from glacial to interglacial epochs. Besides, they took place at higher temperature levels than the climatic leaps in the Quaternary period. That was why they were not accompanied by the sweeping freeze-ups of continents and seas in the northern latitudes.

Even during the Günz epoch (latest Pliocene), the most rigid period in the Pliocene, no ice, except for big mountain glaciers, covered the plains, or the Russian steppes. The freezing in the Upper Pliocene, though generally vigorous, was often interrupted by warming. Four optima were registered in the last million years of the period (Table 11). Just like the Anthropogene optima, they reflected the general process of cooling from Paleogene to modern times. In other words, the thermic level of the optima fell with time.

Table 11

Stages of climatic amelioration in the second cycle

Stage	Equivalent optimum in the Upper Pliocene	Absolute dating, million years	°C above modern annual mean in Central Europe
V	Pre-Apsheron (Günz-Mindel)	0.48-0.55	3.5-4.0
VI	Pre-Günz	0.64-0.80	4.0-4.5
VII	Post-Tegelene	1.0-1.3	4.5-5.0
VIII	Tegelene	1.3-1.7	5.0-5.5

The temperatures in Table 11 characterise the climatic amelioration in each of the four optima. The formation of climate in the past 20,000 years was governed by the same factors as 1,700,000-480,000 years ago. When the temperature of the surface waters in the World Ocean dropped, the climatic conditions deteriorated. That was the direct consequence, as we said, of the heat and water exchange between the Atlantic Ocean and the Arctic Basin. Therefore, by intensifying the exchange, we shall restore the pre-Apsheron through Tegelene optimal climates of the Upper Pliocene.

Proceeding from the climatic conditions which existed 1.5 million years ago, we can make a general prediction of the changes which would result from the climatic amelioration in each of the equivalent stages.

There would be no tundra left on the Arctic coastline save for a narrow strip around Greenland glacial coat. Its place would be taken by coniferous forests near the Pacific Ocean, and deciduous forests, near the Atlantic. Deciduous trees would penetrate into the northwest of Kamchatka and they would drive the conifers out of Eastern Siberia. Thanks to the mild and warm climate, Atlantic species, like hornbeam and beech, would spread in Western Siberia as far as Tobolsk and the adjoining southern regions. The

deserts in Inner Asia would become less arid; in Central Asia they will possibly give way to steppeland.

Subtropical crops would be grown in the regions adjoining the Black Sea from the north, and in the lower reaches of the Don and the Volga. Western Europe would have a more stable climate because of the further reduction in the influx of cold air from the Arctic and the region of the Asian maximum. Similar changes would take place in North America. The climate of semi-deserts and hot, dry steppes of the late Pliocene would be restored in the Sahara, the world's biggest desert, or, at least, in the greater part of it.

But let us get back to the direct flow. What will it be like in the distant future? We know that the present-day mean annual temperature in Central Europe along the Kiev-Warsaw-Copenhagen-Glasgow line is 8°. Tegelene climatic conditions would raise the temperature to 13-13.5°. This rise would be inevitable when the mean annual temperature of the surface waters in Arctic Basin reached 3-4°. Such a temperature can be attained if we pumped about 250,000 cu km/year of warm Atlantic waters into the Pacific Ocean, that is, almost twice as much as would be needed (140,000 cu km/year) to eliminate the Arctic ice sheet and reach the optima of the preceding Anthropogene. But that is almost exactly the volume of the present inflow of waters into the Arctic Basin through the Faeroe-Shetland Strait. Consequently, this volume of warm Atlantic waters would be sufficient to provide for the further warming.

We must mark another important aspect of the envisaged climatic changes. It is the thermal equilibrium between the equator and the North Pole, reminiscent of the Miocene and even Upper Cretaceous. Those epochs had the best climates in the geological history of the Earth. The contributory factors at the time were the intense water exchange between the polar and equatorial basins, the smaller surface of land which was generally lower and had more intricate configurations; and the low albedo of desert vegetation, as compared with the present conditions in barren and arid deserts. But the intensive interlatitudinal water exchange was the most important factor. The polar latitudes were washed by the warm tropical waters.

A rise of one degree in the World Ocean's mean surface temperature is tantamount to a drop of 150-200 metres in the level of continents. By intensifying the mechanical (artificial) water exchange between the polar and equatorial basins, we would regain the advantages lost when the land surface rose by 150-200 metres. We would also compensate the adverse climatic changes produced by the subsequent expansion of land surface. Finally, if we decreased the snow cover, lowered the albedo of the deserts, and so on, we would save much of the heat and humidity squandered.

But that may raise quite a few objections. Some people claim that the rise in the temperature of the World Ocean's surface waters had other causes in the background, such as changes in the solar radiation, and in the composition and pollution of the atmosphere. Although these changes had some effect on the climate in the Cenozoic era, they did so indirectly, through the mechanism in which the surface of the World Ocean played the decisive role. We already know that the fluctuations in the solar radiation only affect the global climate indirectly, through the influence they have on the ocean surface. So in the final count, the causes of the temperature fluctuations of the World Ocean surface are not as important as the fact that it is possible to change this temperature and thereby influence the world climate. Figuratively speaking, how any steam turbine works depends more on the steam parameters than on the system by which the steam is generated, the type of combustion chamber or fuel (atomic, coal, oil, gas, and so on).

In future, a need would certainly arise for greater climatic amelioration on the global scale. It would present no serious problem since the history of the Earth offers a series of climatic optima to choose from. Some of them, indicating the major amplitudinal amelioration stages, are shown in Table 12.

To restore the Cretaceous-Paleocene optimum, the surface waters in the Arctic Basin must have a temperature of 12-14°. Such waters, transferred into the Pacific Ocean, would move southwards in the 200-300-m layer. The present, sufficiently stable stratification would not be affected. Turbulent intermixing with the lower and colder waters is practically ruled out. The surplus warm Atlantic waters coming in from the northwest of the Pacific would be transformed by the surrounding waters, after which they would join the wide circulation in the heart of the northern Pacific. The surplus

Table 12

Stages of climatic amelioration in the third cycle *

Stage	Equivalent optimum in Mesozoic and Cenozoic periods	Absolute dating, million years	°C above modern annual mean in Central Europe
IX	Pliocene	5	6
X	Miocene	20	9
XI	Oligocene	35	12
XII	Eocene	50	14
XIII	Paleocene	65	14
XIV	Upper Cretaceous	80	15.5

* Dating and temperatures are approximate

waters would be carried off first by the Californian, and then by the North Trade-Wind Current towards the western shores of the ocean.

While passing 20,000 kilometres (half the length of the equator) along with the North Pacific and the Equatorial currents, these Atlantic waters would be heated to 29-30° and would enter the straits in the Philippine Islands and flow further westwards. Then with the trade-wind currents of the Indian Ocean they will join the Agulhas Current. At the same time, a sizable stream would be diverted south with the East Australian Current. In the final count, the two streams would join the Atlantic through the circular trade-wind currents. Thus, they would close the World Ocean's circuit of warm surface waters in the northern and southern hemispheres.

So just a single impulse, which would boost the Atlantic-Pacific flow, would ensure the circulation of waters around Africa, Eurasia, America and the Antarctic. The surface waters will be passing through equatorial and frigid zones twice on their way.

The circulation would have two cooling and two warming cycles. In other words, it would resemble a four-stroke, thermal, tandem-binary cycle with the inherent technical and economic advantage: a single fulcrum.

Of course, when the volume of the interoceanic flow is big enough, we would be able to eliminate the temperature

contrast between the equator and the North Pole almost entirely. In that event, the zonal division of vegetation would become blurred since almost the same species and kinds of plants would spread from the subtropics to the former sub-polar zone (with due regard, naturally, for seasonal modifications caused by solar radiation).

In such a warm and humid climate there would be no cold or tropical deserts just as there were no such deserts during the climatic optima of the past.

As to the geological past (400-500 million years ago), the deserts then, as C. Brooks noted, were biological, because there were no plants at that time capable of existing in arid conditions.

The equivalent of the Cretaceous-Paleocene optimum can be attained by transferring at least 450-500,000 cu km/year of warm Atlantic waters through the Arctic Basin. Mankind would be in a position to provide the necessary energy for this purpose not later than the end of the 1980s. But fears are expressed that if the temperature in the Arctic Basin went as high up as 12° or 14°, completely melting the ice in the Antarctic and Greenland, the level of the World Ocean would inevitably rise. However, approximate calculations convince us that the rise would not produce a negative balance in the Antarctic glacier coat. That can be verified from the following. A comparison of the progressive trends in the mean annual temperatures of air in the Antarctic (Little America, 78°12′S) and Arctic (Spitsbergen, 78°14′N) has revealed that the rate in the Arctic was twice as high. In the period from 1911 to 1957, the mean annual rise in temperature in Little America was 0.057°, as compared with 0.139° in Spitsbergen (1912-1954). On these grounds we may assume that in future, if the mean annual temperature at 78°N rose from the present —15° to 14°, the temperature at the corresponding latitude in the Antarctic would rise from approximately —35° to —24°. Even if the temperature at 78°S were to rise higher, say, to —15°, this would not entail a negative balance in the Antarctic ice sheet. This assumption is backed by the observations of the Greenland glacier.

The influence of the other glaciers, with the exception of Greenland, is slight. But the destruction of the Greenland glacier could raise the level of the World Ocean at the rate

of 1-1.5 mm/year. The rate, as has been proved in practice during the last few decades, would not hamper man in his economic activities. In the future, with the expansion in the production of cheap power, man would be able to prevent this rise.

As we see, the climate on the Earth can be improved over and beyond the equivalent optima of the Anthropogene and late Pliocene. Mankind is capable of creating a subtropical climate in the Arctic Basin. Academican P. P. Lazarev has illustrated graphically on his models that similar conditions did exist for a long period of time at the beginning of the Cenozoic era and earlier.

CONCLUSION

Poor harvests due to unfavourable climatic conditions prompted man to work out methods of influencing the climate to reduce the dependence of agriculture on Nature's whims to a minimum. In the attempts to solve the problem, researchers hit on the idea of the global climatic amelioration.* An analysis of paleogeographic materials undermined the myth of the conservative nature and the inertia of the climate.

An analysis of modern data on the dynamics of climate leads to the following conclusions.

Large-scale climatic changes from the coldest and, therefore, the most arid climate of maximum glaciation, to any of the climatic optima in the Anthropogene can be affected by a simple change in the thermal conditions of the surface of the Arctic Basin. The higher the temperature there, the smaller the thermal contrast between the equator and the pole. The interlatitudinal equalisation of temperature in the past was always accompanied by climatic amelioration, all over the world, including the USSR. The biological productivity of the lands also improved everywhere, from tropical deserts to the coldest zones in the Polar Circle.

The principal factor in the formation of the thermal régime in the Arctic Basin is the water exchange with the Atlantic. When the exchange is intensified, the temperature of the basin's surface rises, the ice cover disappears, and the radiation balance drastically increases. Without a a fixed minimum of heat from sea advection, there can be no stability in the ice-free state of the basin. The ice cover,

* The first work of this kind, called "Radical Improvement of Climate in the Planet's Polar and Moderate Latitudes", written by the author of this book, was filed at the USSR Committee for Inventions and Discoveries of the USSR Council of Ministers under No. 7337 in 1957.

which is always inclined to expand on its own, regenerates quickly.

A rise in the temperature of the Arctic surface waters releases a chain reaction of similar rises in the World Ocean, primarily in the North Atlantic. Evaporation and atmospheric humidity increase, causing greater precipitation over the continents. So, in the past, substantial temperature rises in the Arctic supplied the continents with more heat and water.

These laws help us to solve the problem of the stage-by-stage reinstatement of the climatic conditions which prevailed in the Upper Anthropogene and Pliocene. The easiest way of doing this is by conducting the Atlantic waters to the Pacific Ocean by way of the Arctic Basin. It would be an imitation of Nature's own large-scale climatic amelioration methods that guarantees the feasibility of the project. The direct flow can be set into motion even at our present level in hydroengineering.

The project is technologically feasible, technically clear, and is simple in concept. It can regulate the sea advection of heat practically to any extent desired. The modern level of engineering—the building industry, mechanical engineering, power engineering, automation and so on—is equal to the task. It is all up to the international co-operation between scientists and governments, particularly in the USSR, USA and Canada.

Mankind wastes tremendous amounts of labour and material resources in overcoming the difficulties created by the unfavourable climates. The losses mount as the population increases and man's economic activities expand and increase in complexity. They already considerably exceed the capital investments that would be needed to bring back the excellent climatic conditions of the past. It is high time to stop wasting our energies on local amelioration. The practice is as backward as the promotion of the horse in place of the railway, car and plane would be.

The erroneous idea that the project would need more electricity than we could provide, has prompted some research workers to try to solve the problem by such unreliable and limited methods as local modifications in the oceanic bed, painstakingly covering the sea surface with black powders, installing heating devices, and so on.

Today such countries as the USSR, USA and Canada commission an overall capacity of power far in excess of that required for the interoceanic water transfer every year. And we must not forget that the increment in precipitation over the continents which would follow as a result of the greater evaporation from the World Ocean, would increase the shore drainage. This would boost the output of the already existing hydroelectric power stations with virtually insignificant additional outlays. According to calculations, this extra electric power would in itself be more than enough to cover the needs of all stages of the project. The electric power used would be reimbursed "in kind". So the power expenditures need not be taken out of any country's power balance, or, for that matter, from the sum of the balance of all countries. The hydroengineering complex in the Bering Strait should be regarded as a unique power scheme for the greater utilisation of the solar thermal radiation and its partial conversion (through the evaporation-precipitation-drainage cycle) into electric power at already existing and projected hydroelectric power plants all over the world.

The incorrect notion that there is a shortage of electric power imbues the agencies responsible for planning the research work with conservatism. The gap between our actual potential for the large-scale climatic amelioration and the state of research work widens every year. In the meantime, Soviet and foreign scientists are predicting that the last decades of this century are threatened with a serious deterioration of climatic conditions.

Having carefully examined the age-long fluctuations in the state of ice in the North Atlantic, I. V. Maksimov warns that in the next few years we should expect an increase in the glaciation and the return of rigorous winters and hot, drier summers. The climate will once again take a turn for the worse, just as it happened at the beginning of the last century. After analysing the solar activity in the past centuries, M. S. Eigenson has arrived at the conclusion that the expansion of the ice cover in the polar seas is unavoidable in the next few decades.

L. A. Vitels believes that the last three decades in the 20th century and, possibly, the beginning of the 21st century will be marked by a drop in solar activity. He recommends precautions in the long-term planning of everything that

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This book examines the ways to solve
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the suggested projects
for reforming Nature and the possibilities
of putting them into effect.